Open Issues in Heavy-Ion Physics: Symposium in Honor of Guy Paic
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Recent issues on radiative energy loss

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Contents:

1. Introduction: the formalism and LHC data.

2. Energy-momentum conservation.

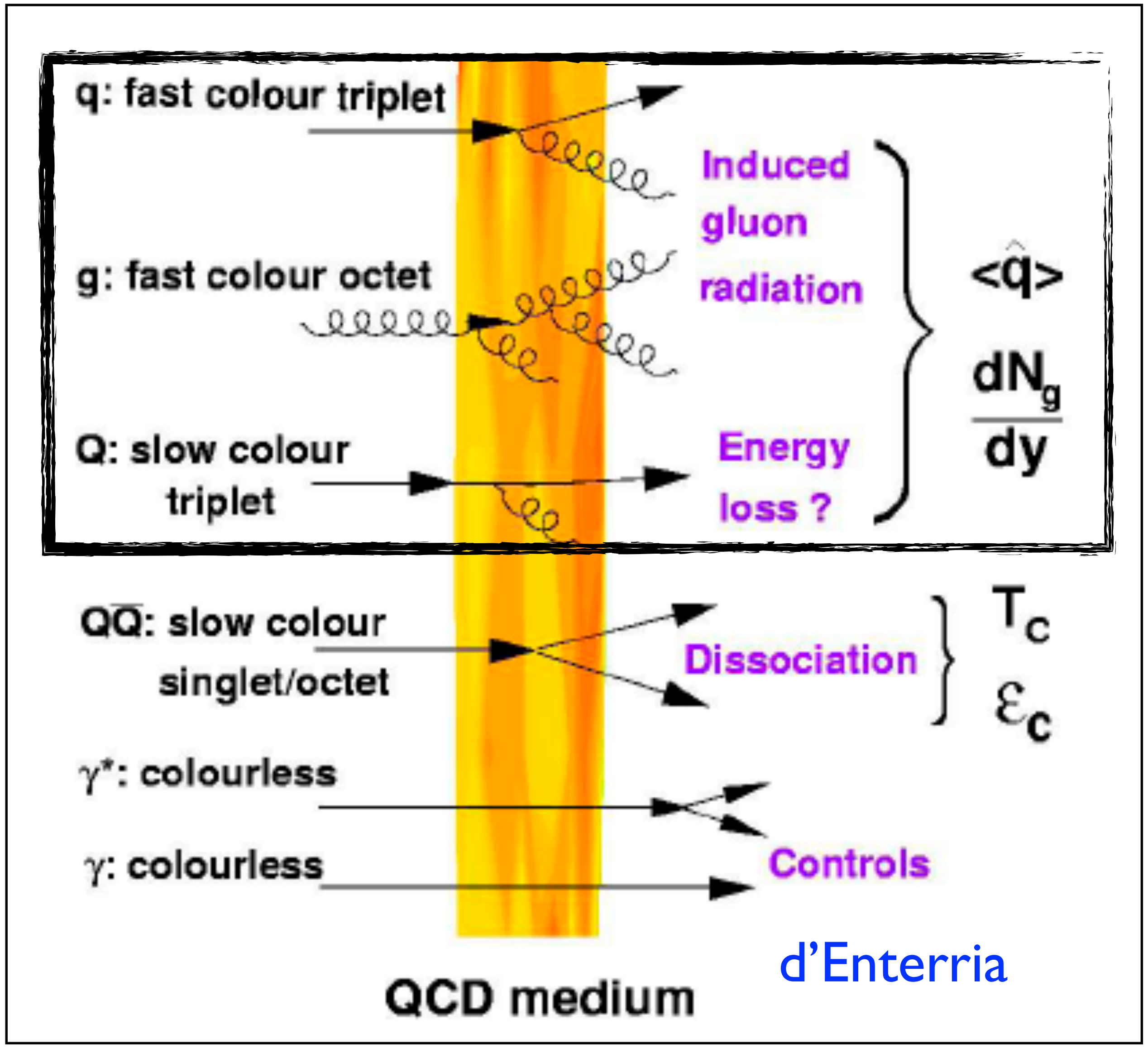
3. Interplay with elastic energy loss.

4. Embedding in a medium.

5. Building jet calculus in a QCD medium.

Disclaimer: this is a biased personal (re)view, intended for a not-too-restricted audience.

See the plenaries by Konrad Tywoniuk at HP2012 and Guilherme Milhano at QM2012.



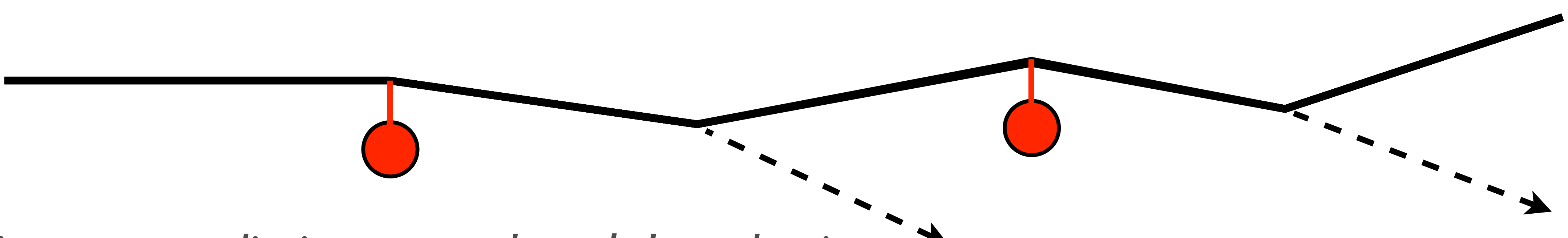
d'Enterria

Medium effects on QCD radiation:

- In high-energy heavy-ion collisions, collinear factorization (for $Q \sim E_{cm} \gg \Lambda_{QCD}$) assumed to hold in medium, with nPDF's evolved using DGLAP and medium-modified fragmentation functions:

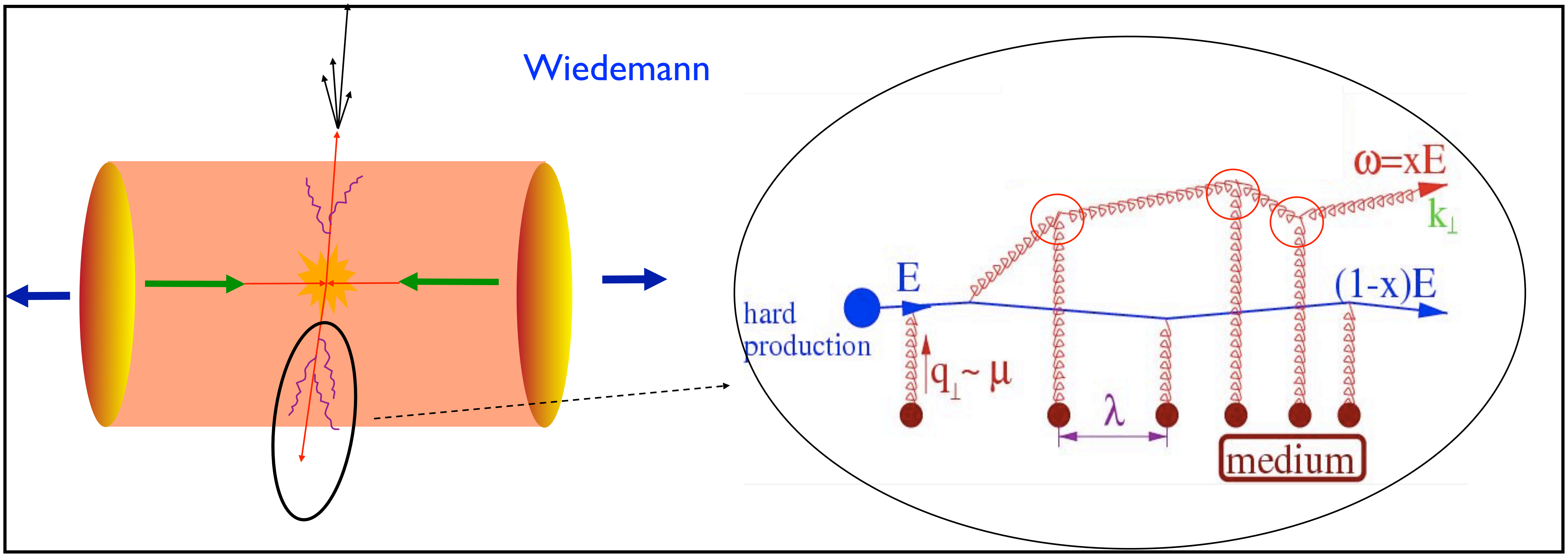
$$D_{i\to h}^{med}(x,Q^2)=\int_0^1 \frac{d\epsilon}{1-\epsilon}\,P(\epsilon)\,D_{i\to h}^{vac}\left(\frac{x}{1-\epsilon},Q^2\right)$$

- Fragmentation like in vacuum: outside the medium which should be true for large energies (or p_T for η=0).
- P(ε): probability to lose some energy (quenching weights) by any kind of energy loss mechanism, either collisional through multiple collisions, or radiative through multiple gluon emission. The latter is suppose to be the dominant phenomenon at large energies.



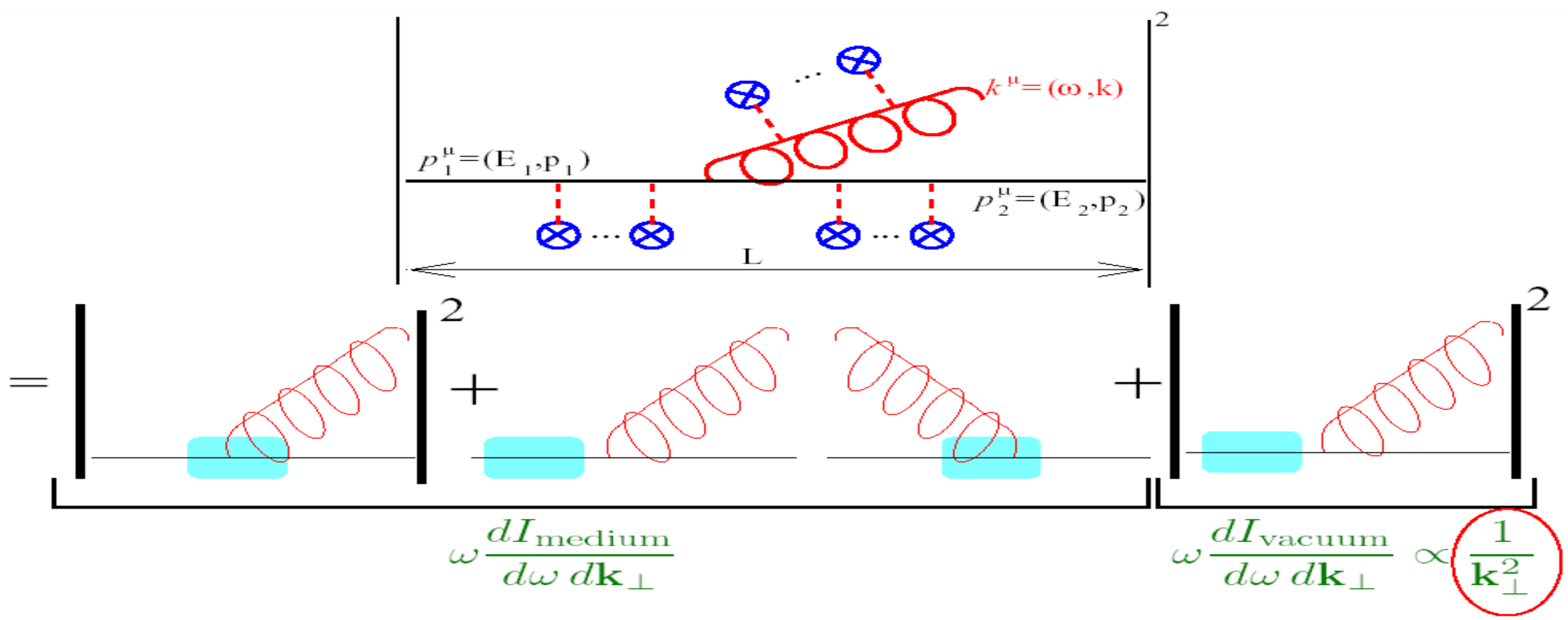
Models:

Medium-modified gluon radiation through interference of production and rescattering.



Two parameters define the medium: one characterizing the density and strength of interactions with the medium, plus the length (geometry, dynamical expansion).

Radiative eloss: qualitative arguments:



- $\Delta E/L \propto \langle k_T^2\rangle$: energy loss linked to broadening.
- Large $t_{form} \sim L$.
- Semihard $\omega \sim \omega_c$, large $\theta \sim (\hat{q}/\omega^3)^{1/4}$ radiation.

Consider the de-coherence process |qg> → |q>+|g> and define the transport coefficient qhat=μ^2/λ.

$$\phi = \frac{k_T^2}{2\omega}\Delta z \sim 1 \Rightarrow \omega, k_T^2 \ll 1 \ \text{ suppressed} \qquad \phi \sim \frac{\hat{q}L}{2\omega}L = \frac{\omega_c}{\omega} \sim 1 \Rightarrow \omega > \omega_c \ \text{ suppressed}$$

⇒ IRC safe!!!!

$$\hat{q}t_{coh} \simeq \frac{\hat{q}\omega}{\langle k_T^2\rangle} \simeq \langle k_T^2\rangle, \quad \langle k_T^2\rangle \simeq \sqrt{\hat{q}\omega}$$

$$-\frac{dE}{dz} = \int d\omega \frac{1}{t_{coh}}\,\omega\,\frac{dI}{d\omega}\bigg|_{1\ scat} \simeq \alpha_s C_R \int^{\omega_c} d\omega \sqrt{\frac{\hat{q}}{\omega}} \Rightarrow -\Delta E \propto \alpha_s C_R \hat{q} L^2$$

Radiative eloss: limitations

• The extracted value of qhat depends on medium model $1<\hat{q}<15$ GeV^2/fm ⇒ interface with realistic medium.

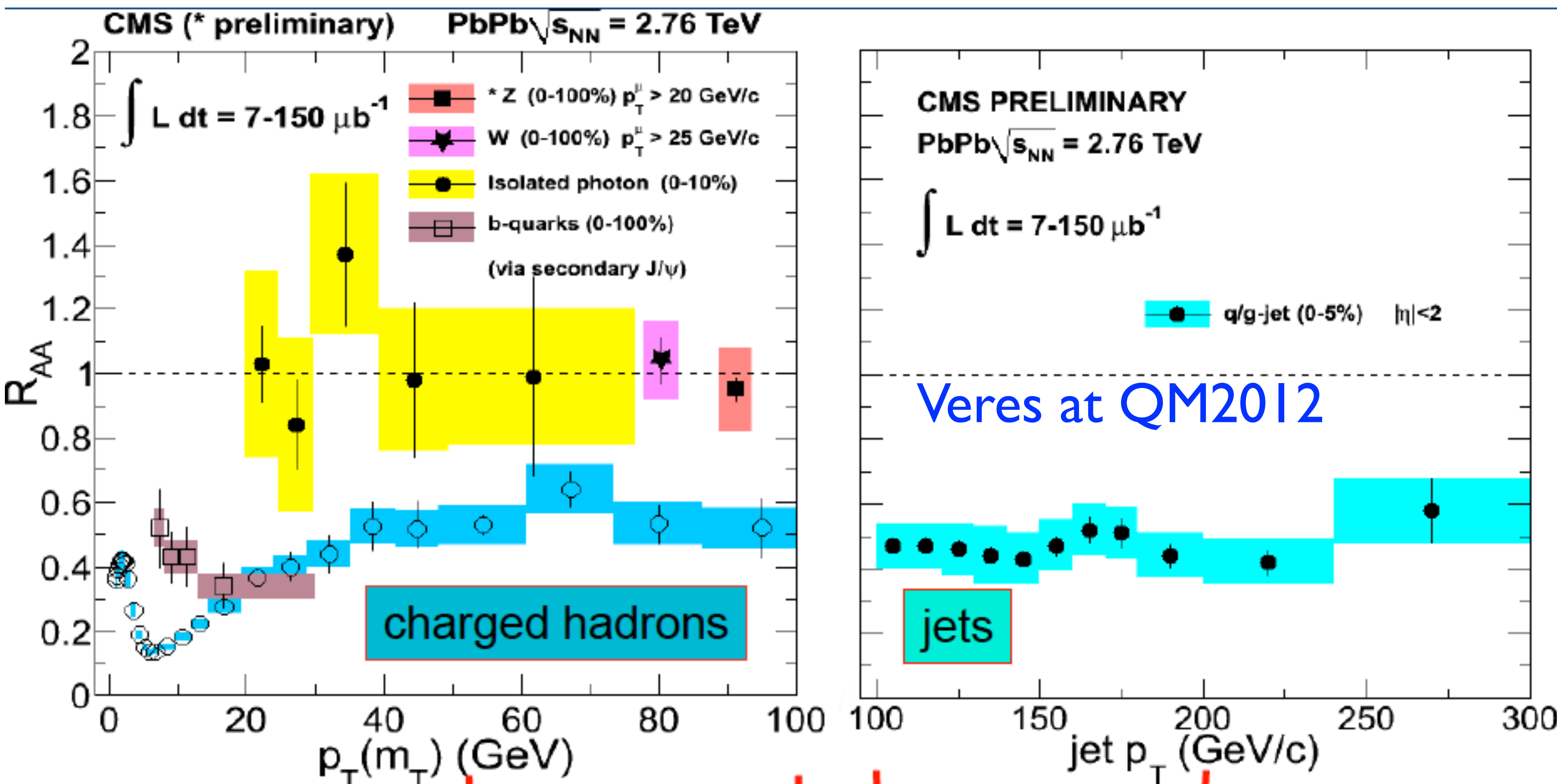
• Calculations done in the high-energy approximation: only soft emissions energy-momentum conservation imposed a posteriori ⇒ Monte Carlo.

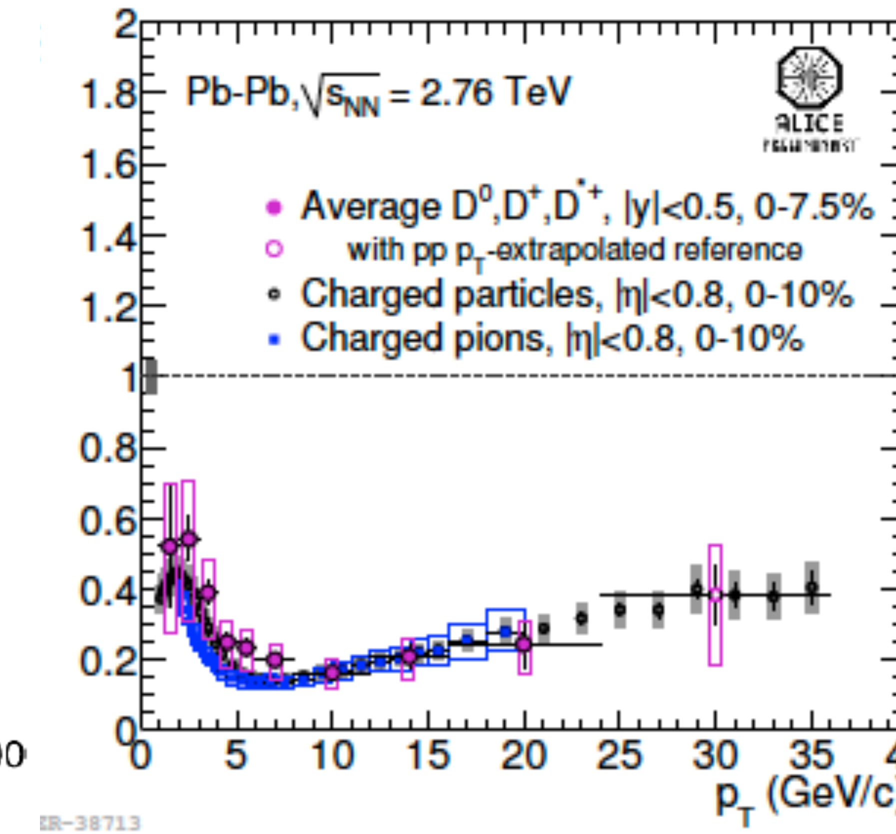
• Multiple gluon emission: Quenching Weights independent (Poissonian) gluon emission: assumption! ⇒ Monte Carlo (PQM, PYQUEN, YaJEM, JEWEL, Q-PYTHIA).

• No role of virtuality in medium emissions; medium and vacuum treated differently ⇒ modified DGLAP evolution.

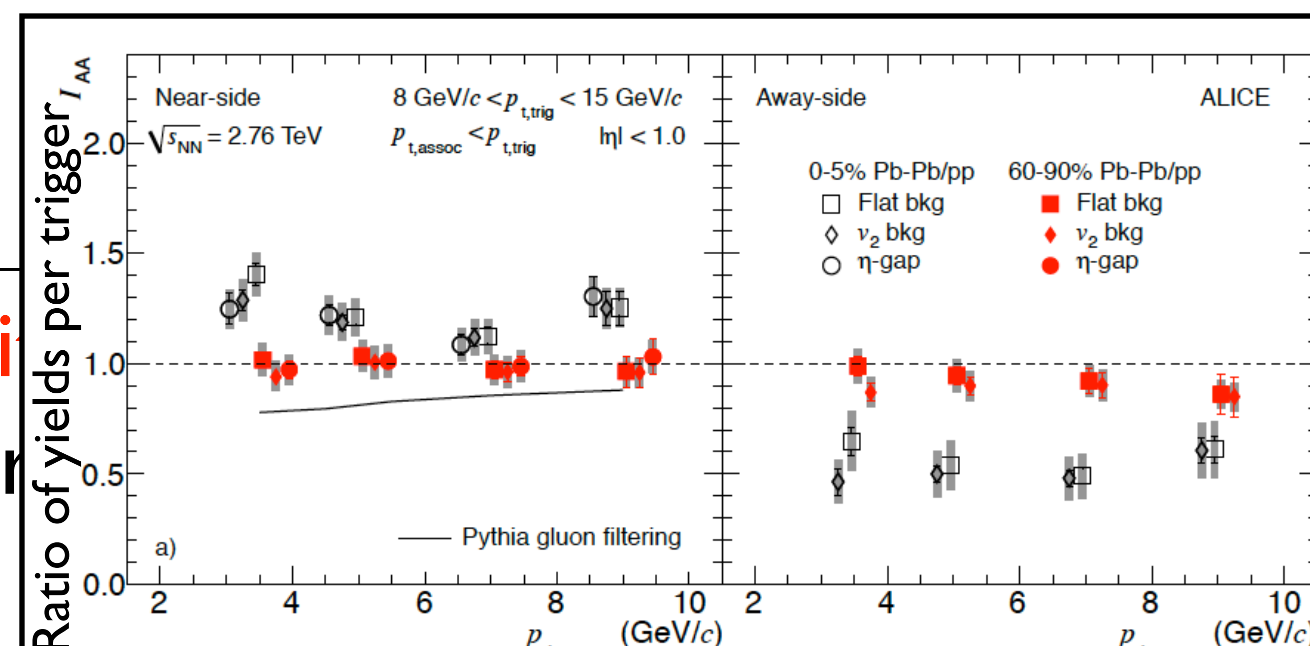
Results for particles:

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\,(1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$





Sampling the ~same parton p_T range



- Behavior compatible wi
- Similar for charged hadr
- Reference crucial!!!

Results for particles:

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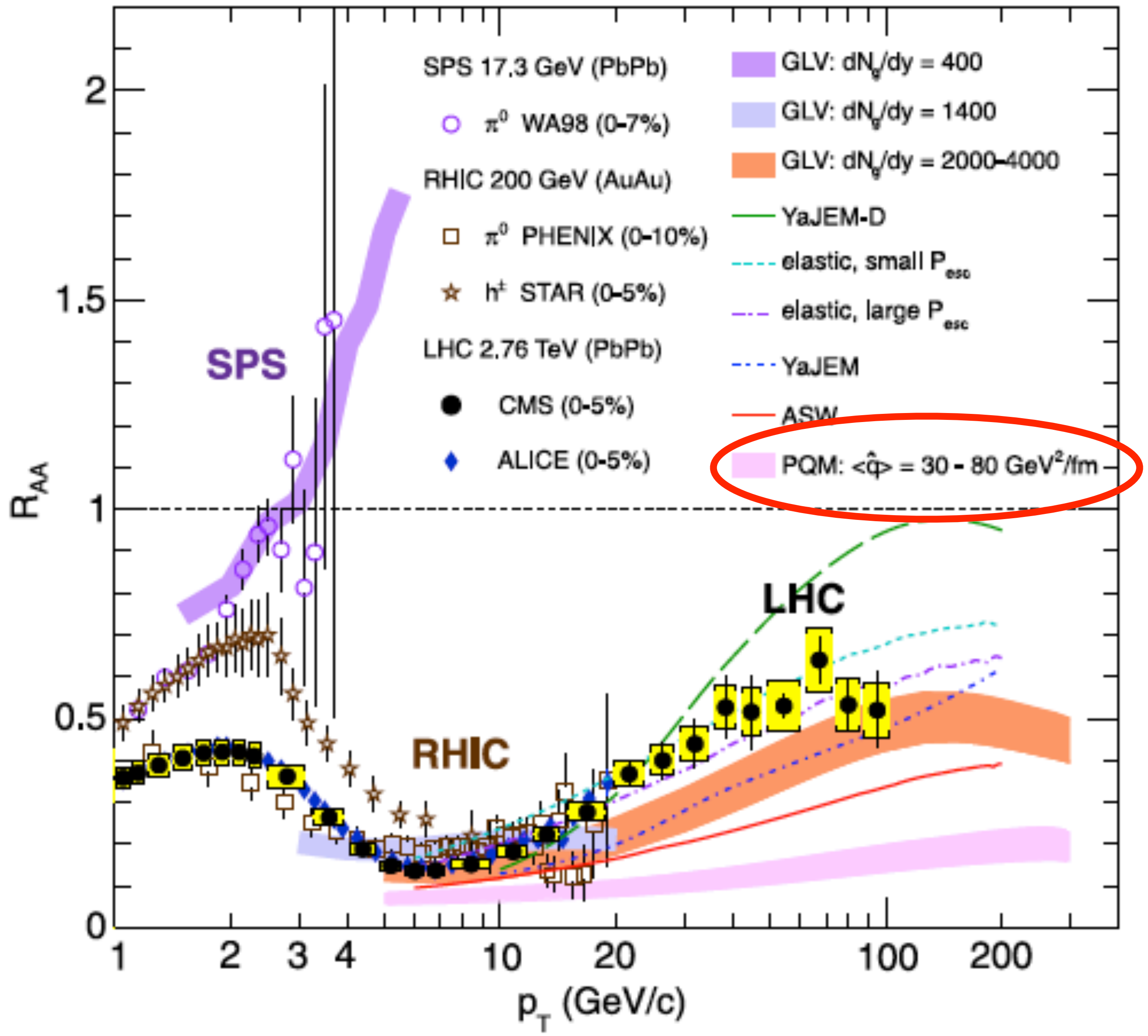
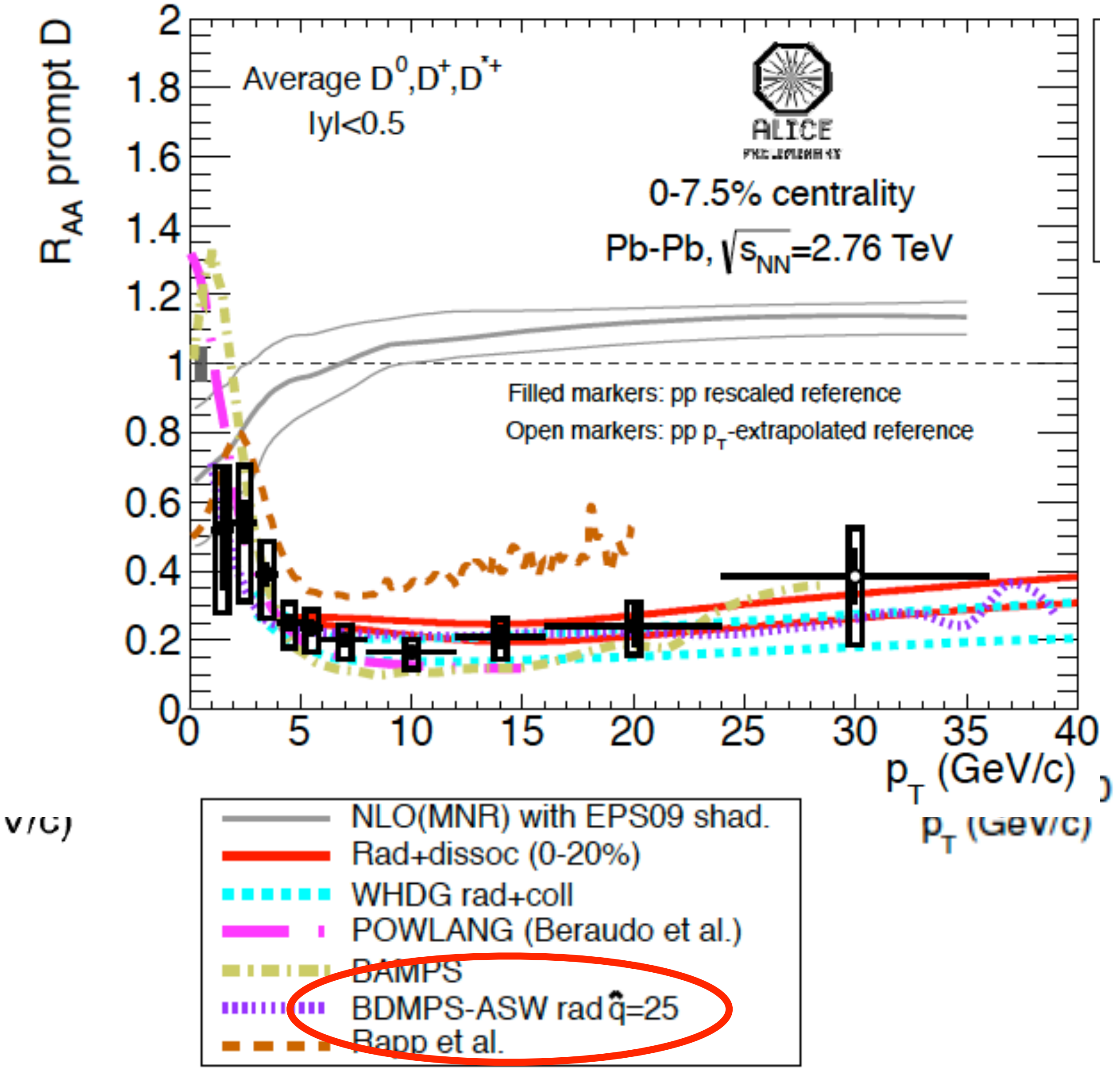
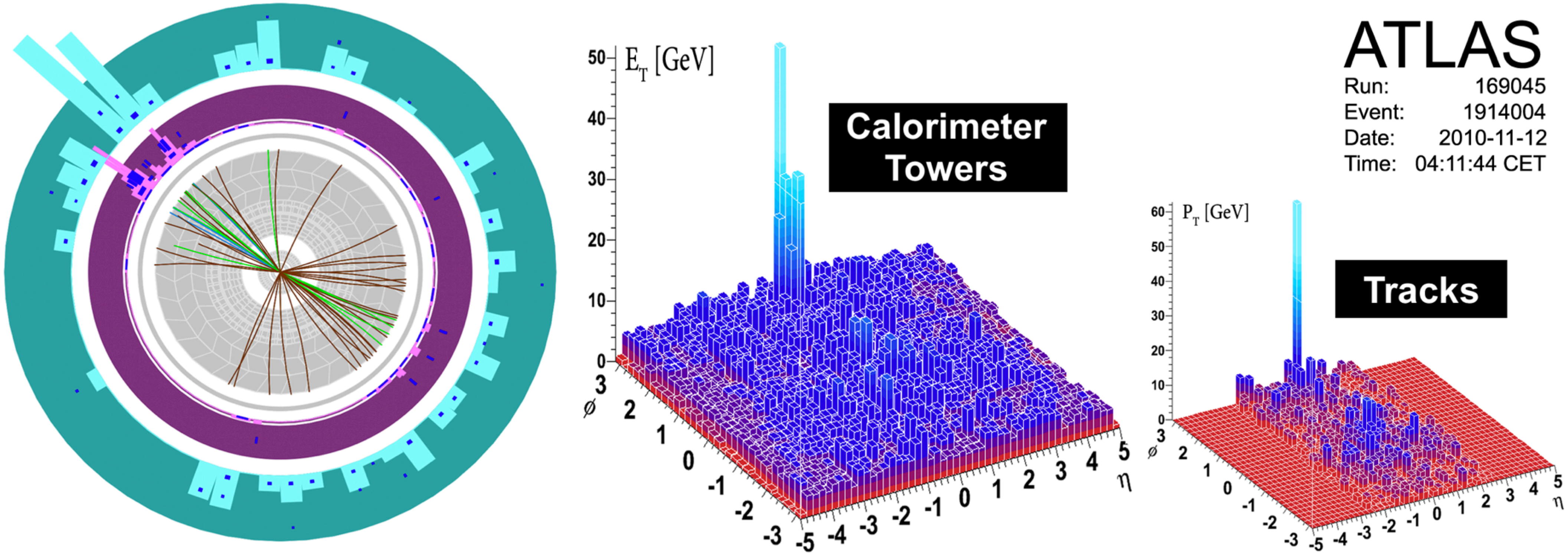




- Behavior compatible with radiative eloss.
- Similar for charged hadrons, for D's, and for jets.
- Reference crucial!!!

Jets:



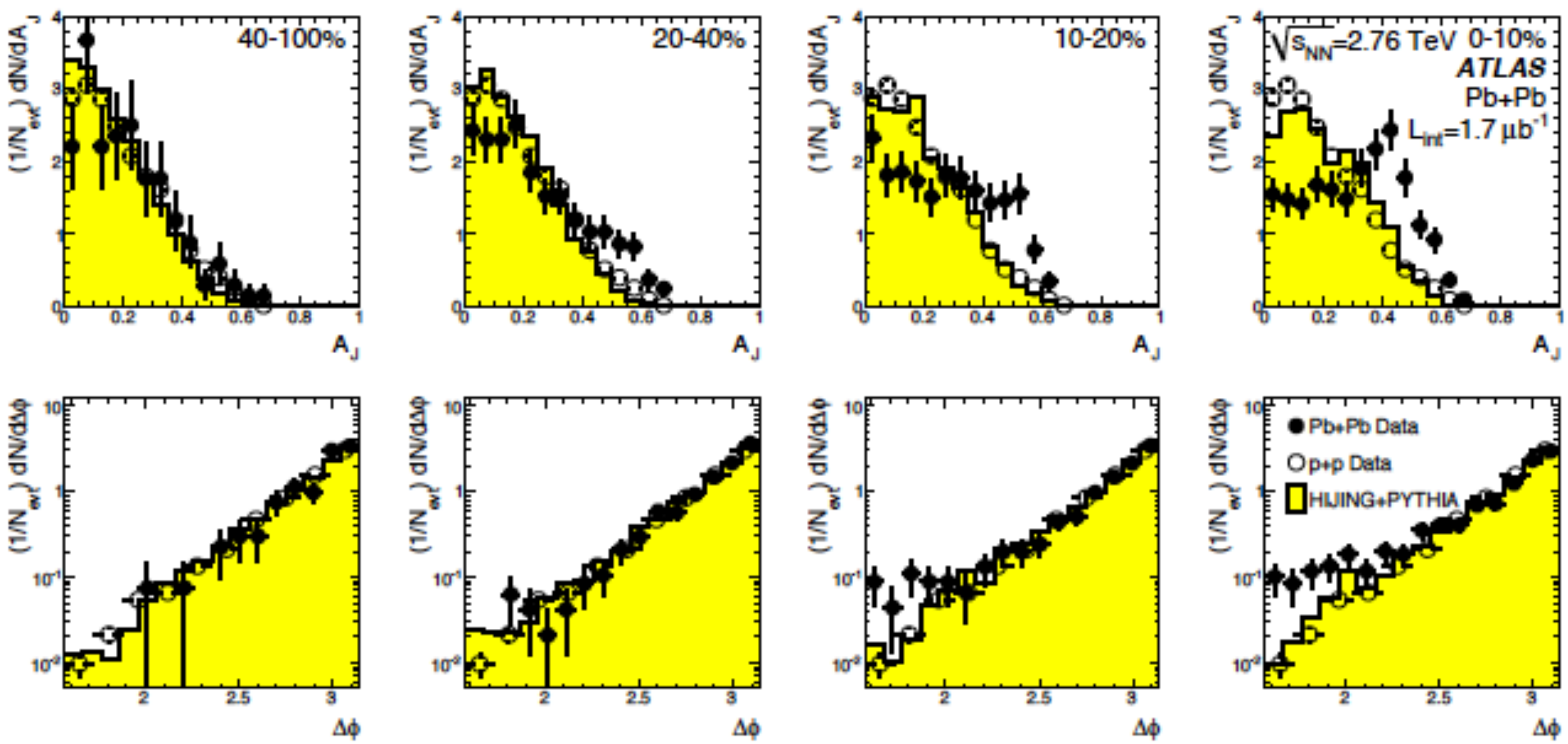
anti-k_T, D=0.4

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

$E_{T2} = E_{T1}/2 \Rightarrow$

$A_J = 1/3$

- CMS got similar results, plus particles.



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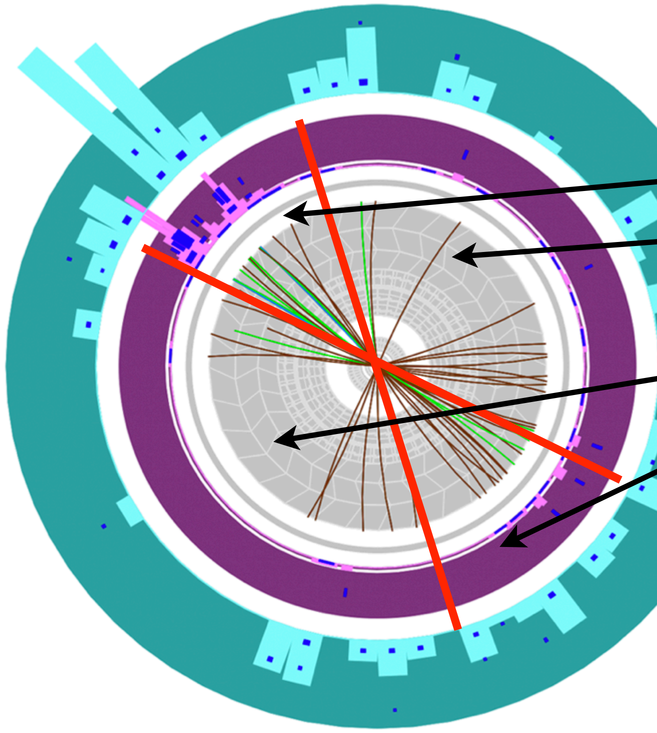

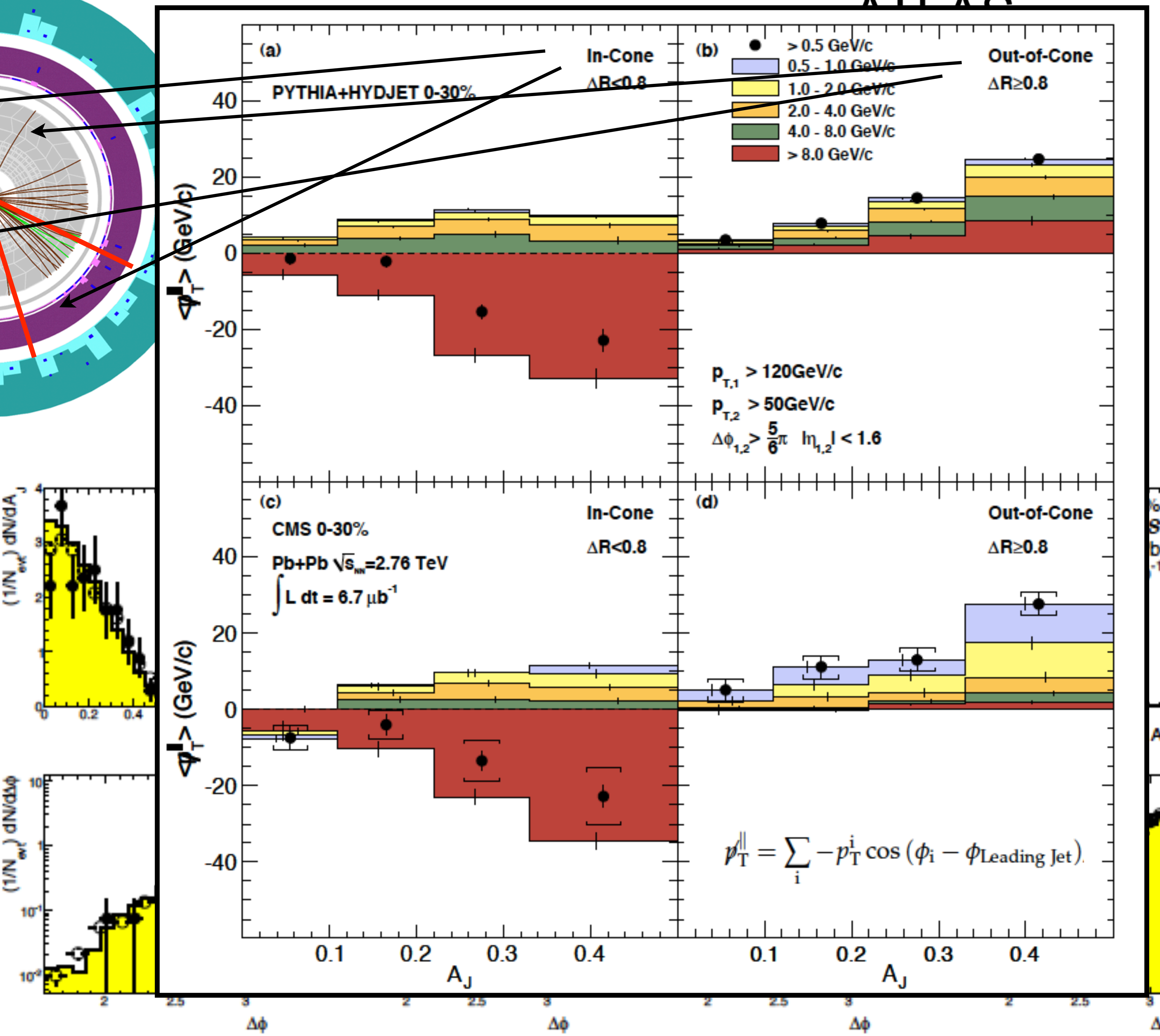

$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos(\phi_i - \phi_{\mathrm{Leading\ Jet}})$$

anti-k_T, D=0.4

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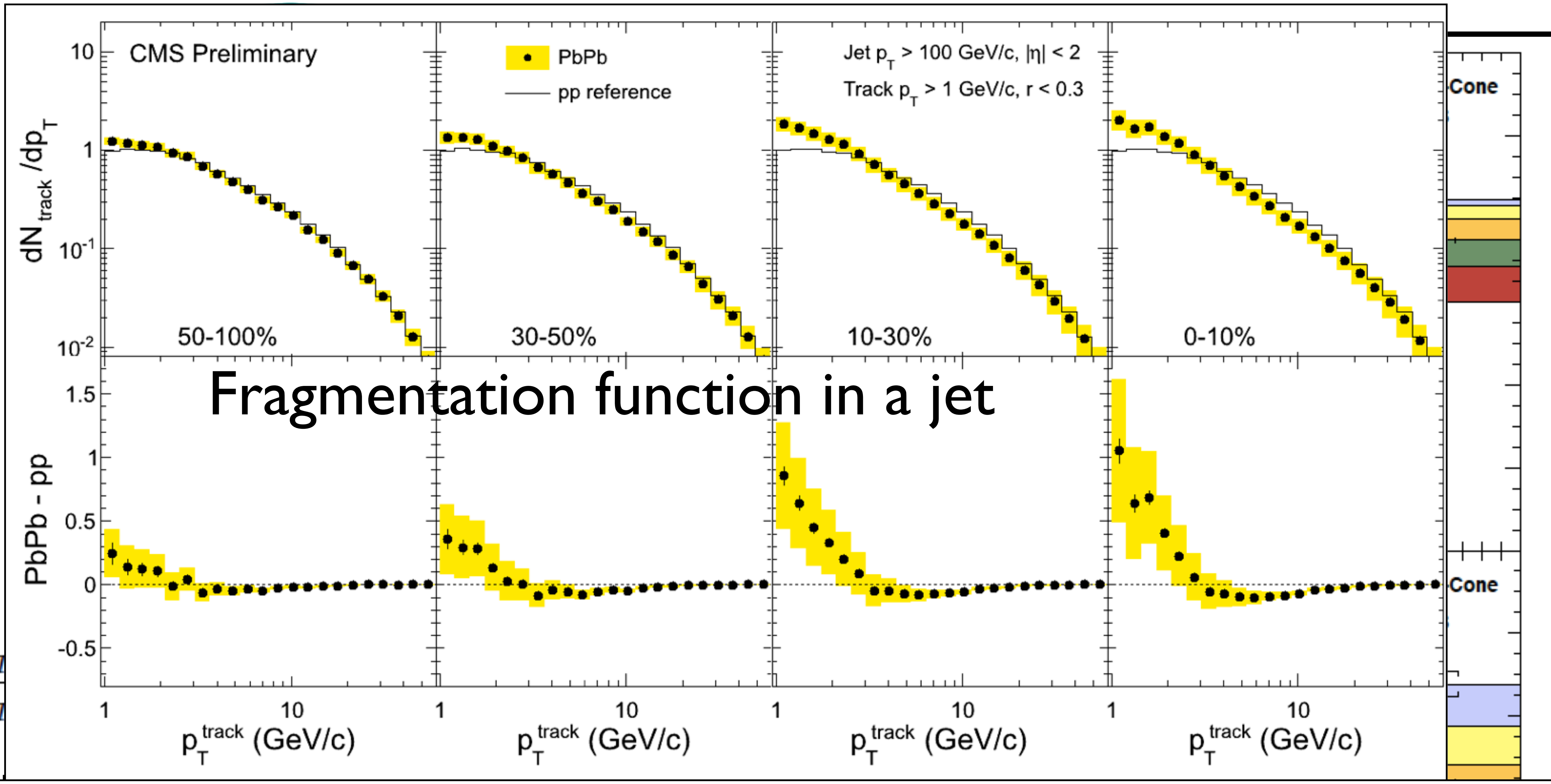

anti-

$A_J = \frac{E_T}{E_T}$

Jets at the LHC: energy loss without broadening via large angle soft radiation, no modification of the hard part of the fragmentation functions: challenge for standard radiative picture? (but multiple splittings + energy conservation have a large effect, Apolinario et al '12).

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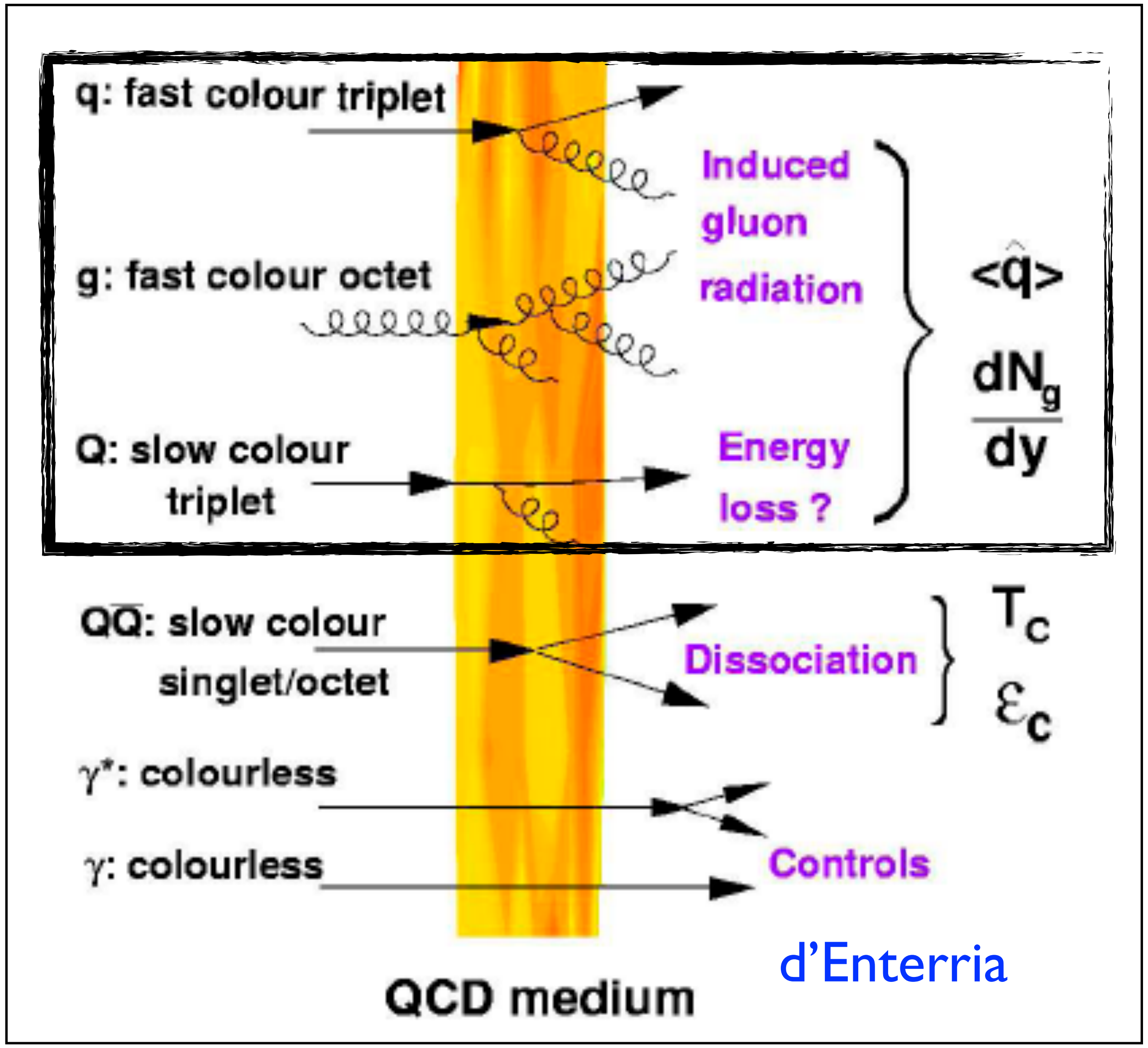
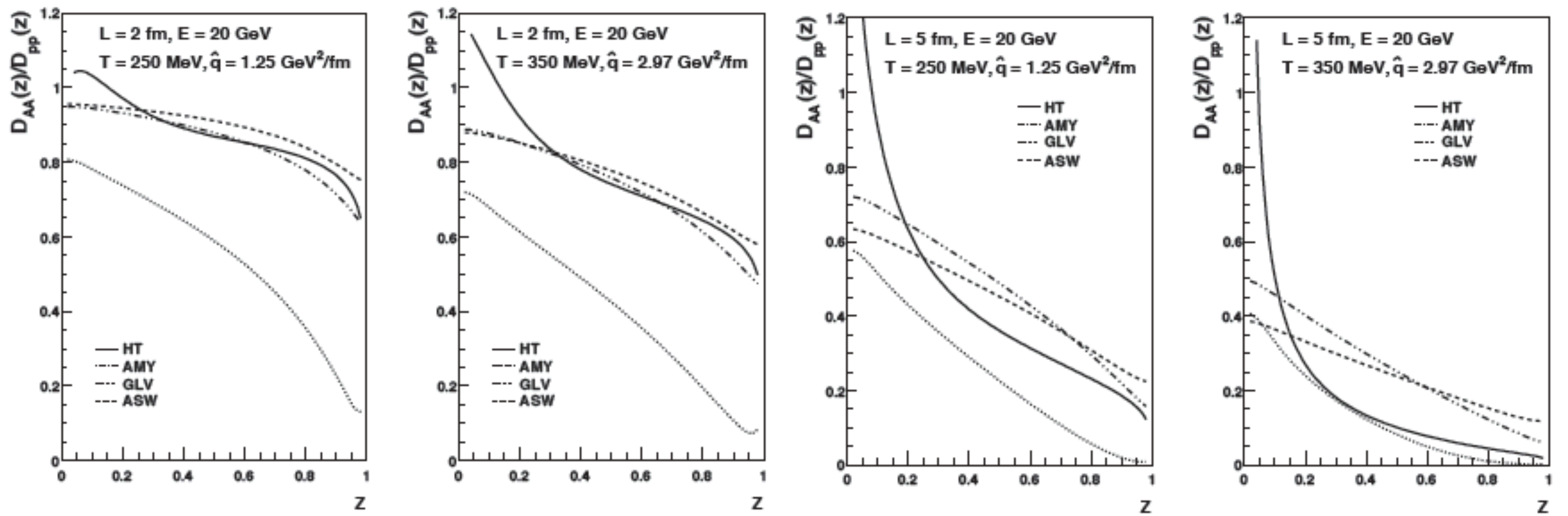


Relevance on implementations:

- Calculations done in the high-energy approximation: only soft emissions, energy-momentum conservation imposed a posteriori ⇒ discrepancies between models (TECHQM '11).



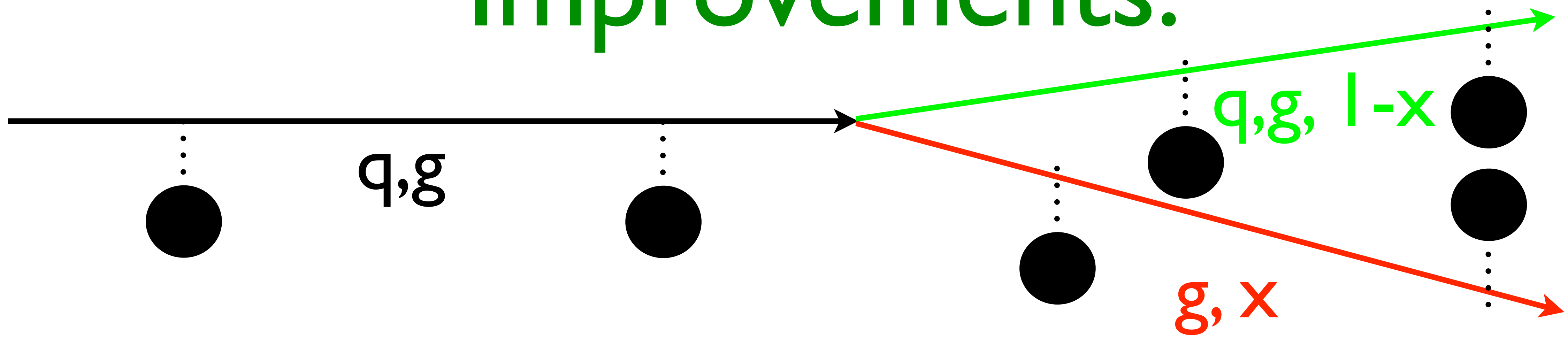
medium modification of quark fragmentation function

$\mu \sim k_T << \omega << E$

Majumder & van Leeuwen [1002.2206]

- Opacity expansion: single hard valid for thin media, multiple soft for thich ones (Caron-Huot et al '10).
- One way out: Monte Carlo, but how solidly grounded is it?

Improvements:



- Current models: x<<1, hard lines are eikonal (Wilson lines, color rotation), soft lines quasi-eikonal (non-eikonal Wilson lines, color rotation plus transverse momentum broadening).

- Next step: all legs quasi-eikonal, complicated color structures: (Apolinario et al '12, Blaizot et al '12).

- Use of SCET: some recoil can be considered (d'Eramo et al '10, Vitev et al '10).

- Further: full recoil, elastic and radiative processes on the same footing.

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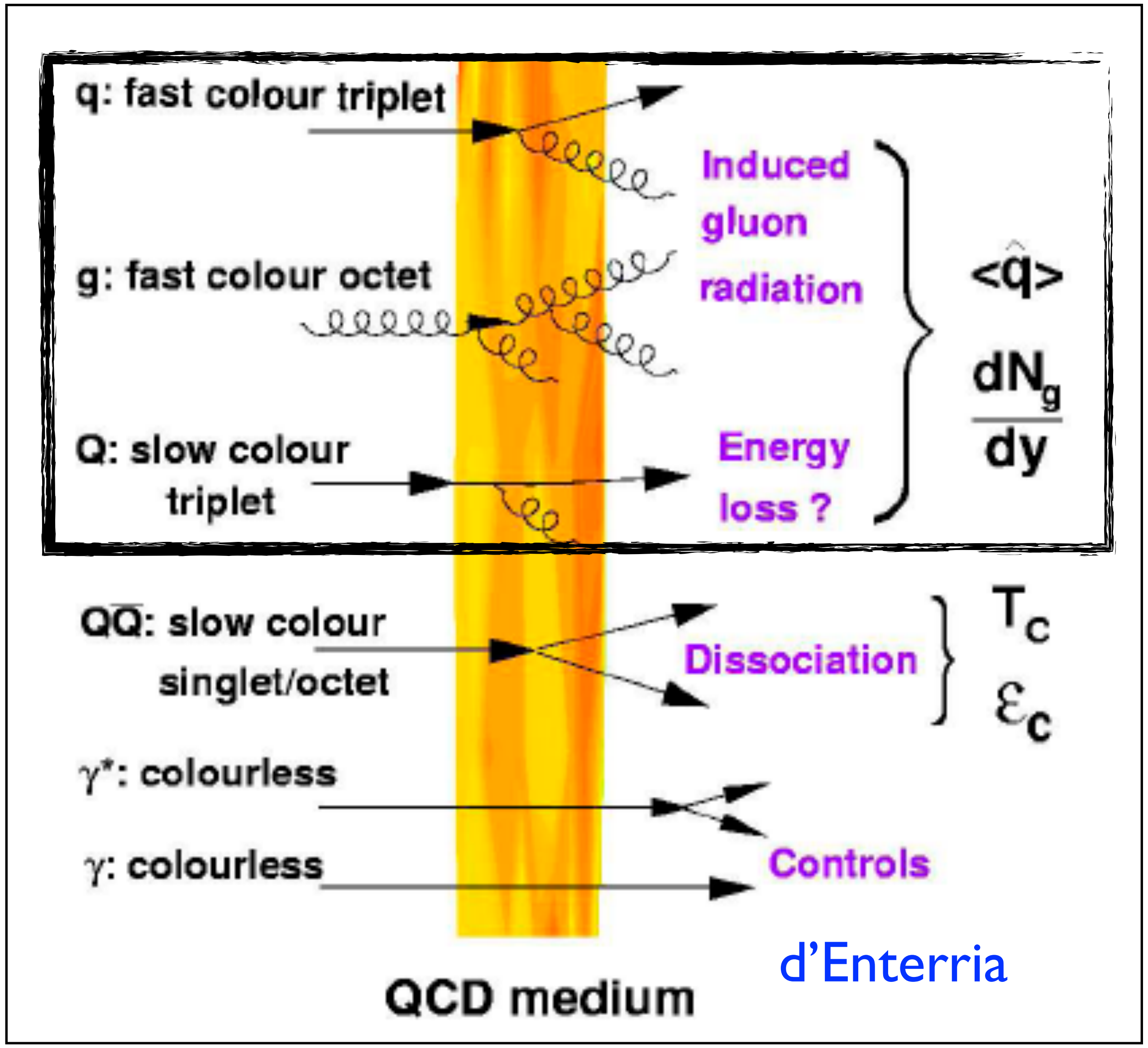

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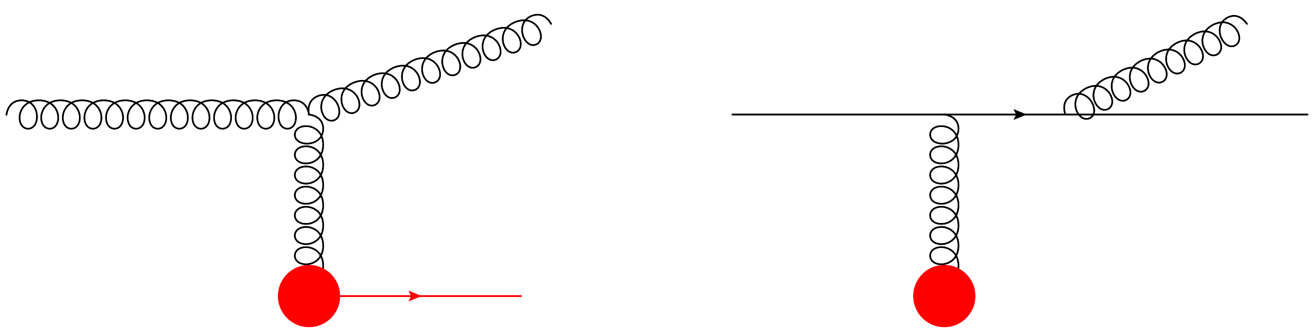
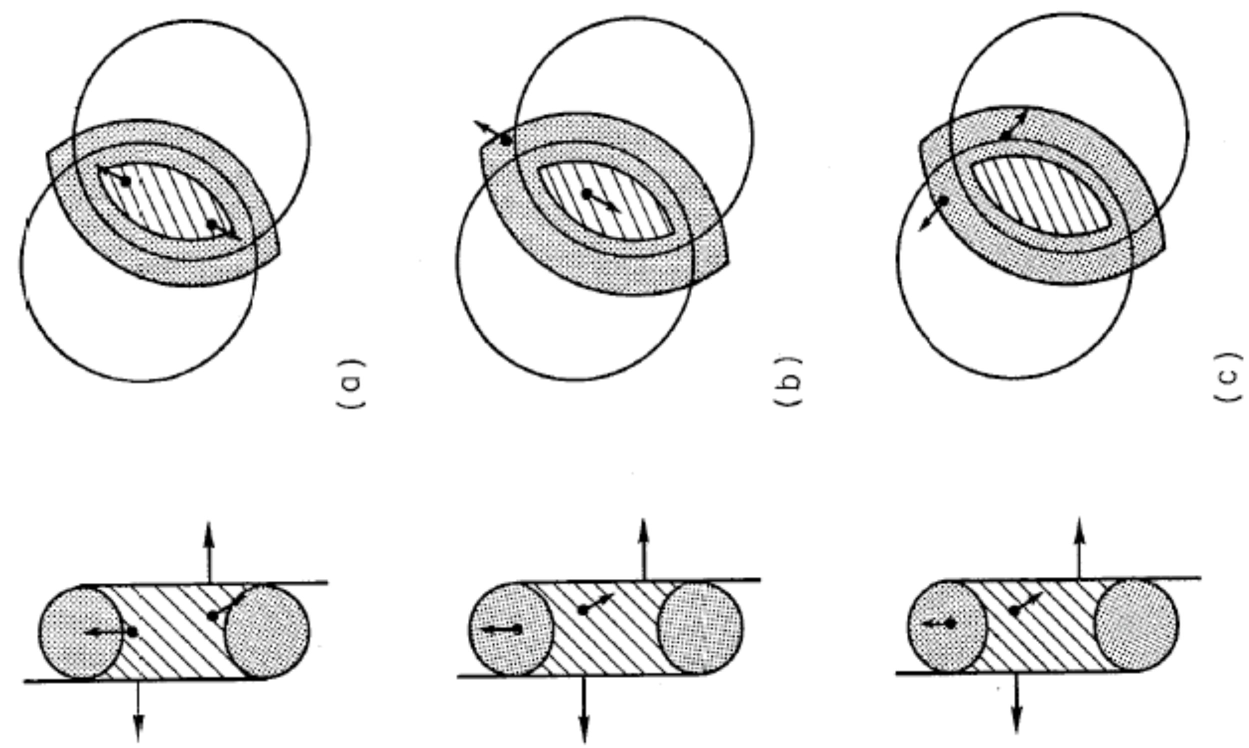
Elastic eloss:

• Elastic means admitting recoil of the scattering centers: more exact kinematics 2→2 and 2→3. Historically first but considered small.





• Essential for: medium response (Mach cones and alike) and heavy partons.

• Standardly: 2→2 matrix elements IR-regulated by ThFT arguments, to compute a elastic eloss probability to convolute with the radiative one, DGHW model.

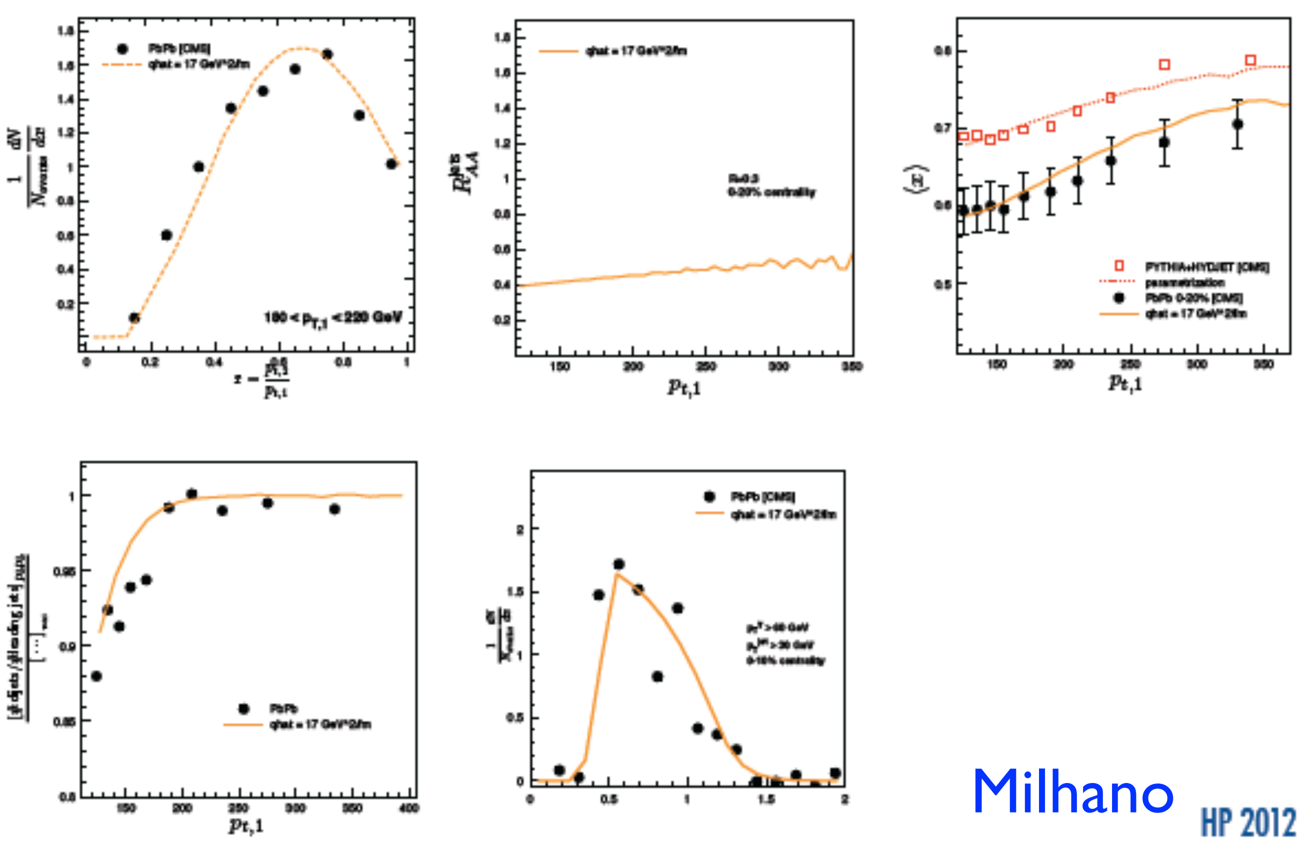
• Going from static to thermal medium changes the potential (Djordjevic '06); also new ehat~<$p_{||}$> (Majumder '09).

• Further steps: Monte Carlo (BAMPS and JEWEL, YaJEM), AdS/QCD.

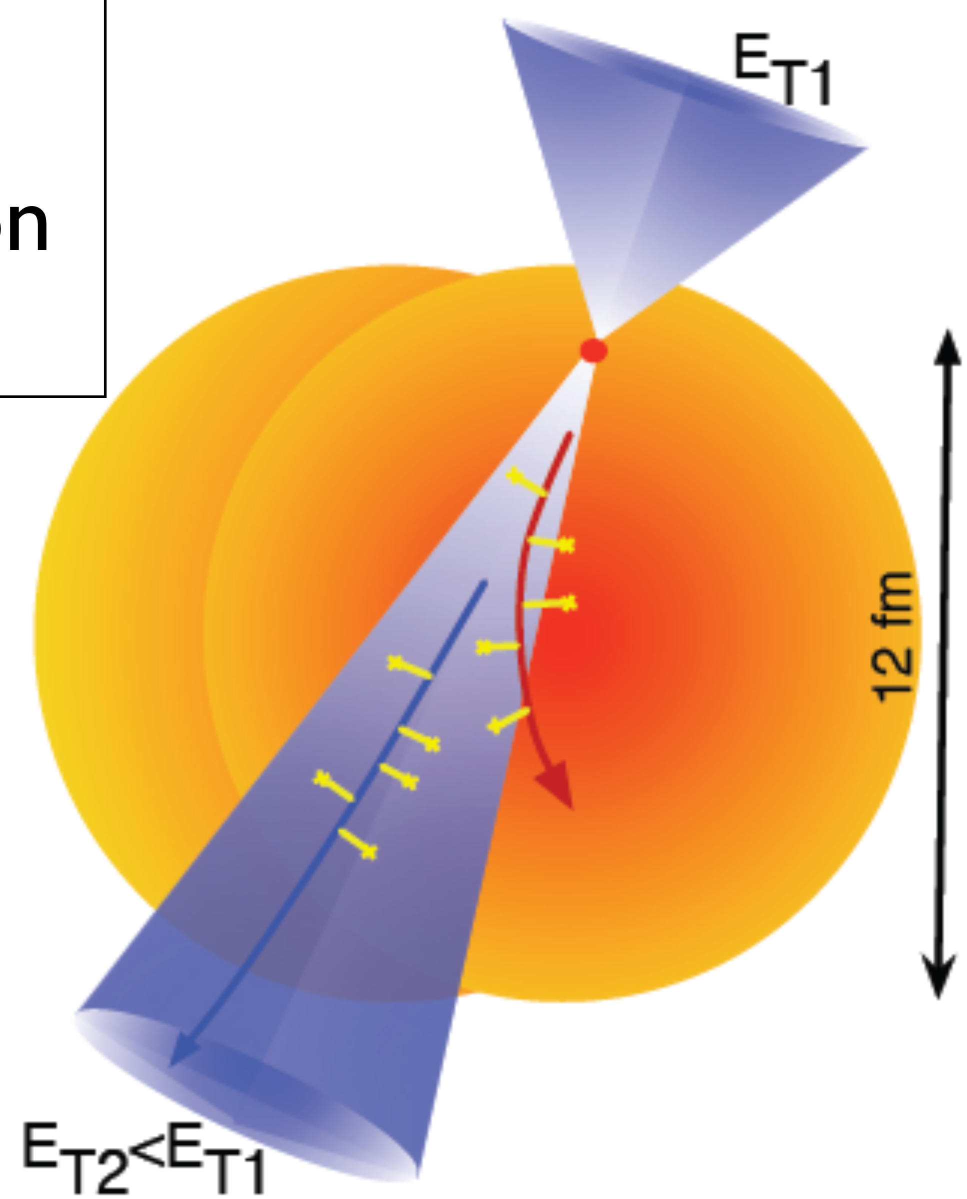
Collimation:

- Small kick to the gluons which go ‘out-of-cone’ may lead to this additional jet-energy ‘degradation’.
- $E_{gluon} < \sqrt{\hat{q}L}$ gives qhatL=50-100 GeV^2, in rough agreement with RHIC extrapolations.
- In pp there is already a lot of degradation ($\langle x \rangle = \langle E_{T2}/E_{T1} \rangle$) differs ~ 10 %).

Casalderrey-Solana, Milhano, Wiedemann, ’10-; Qin and Müller, ’11



Milhano HP 2012



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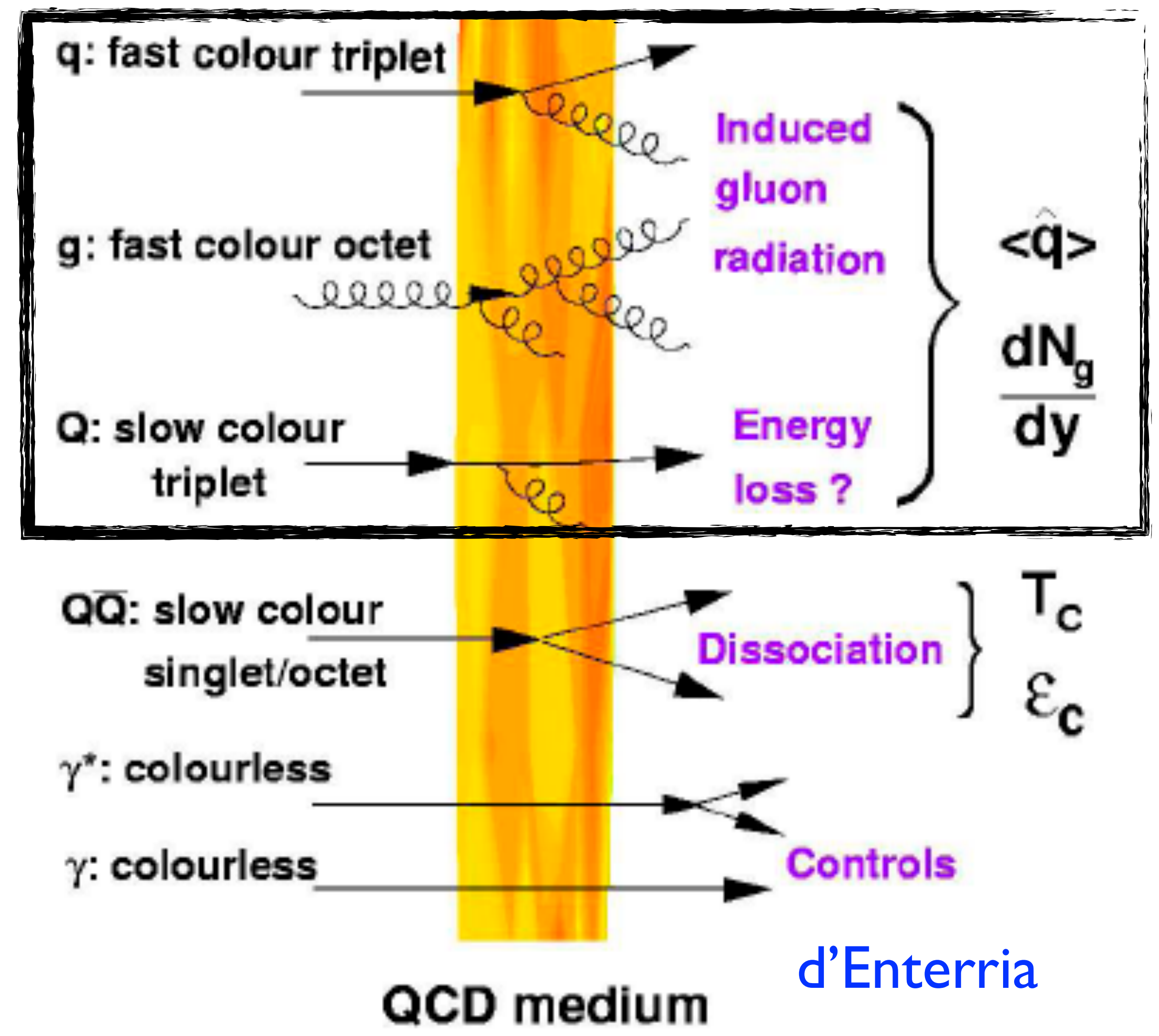

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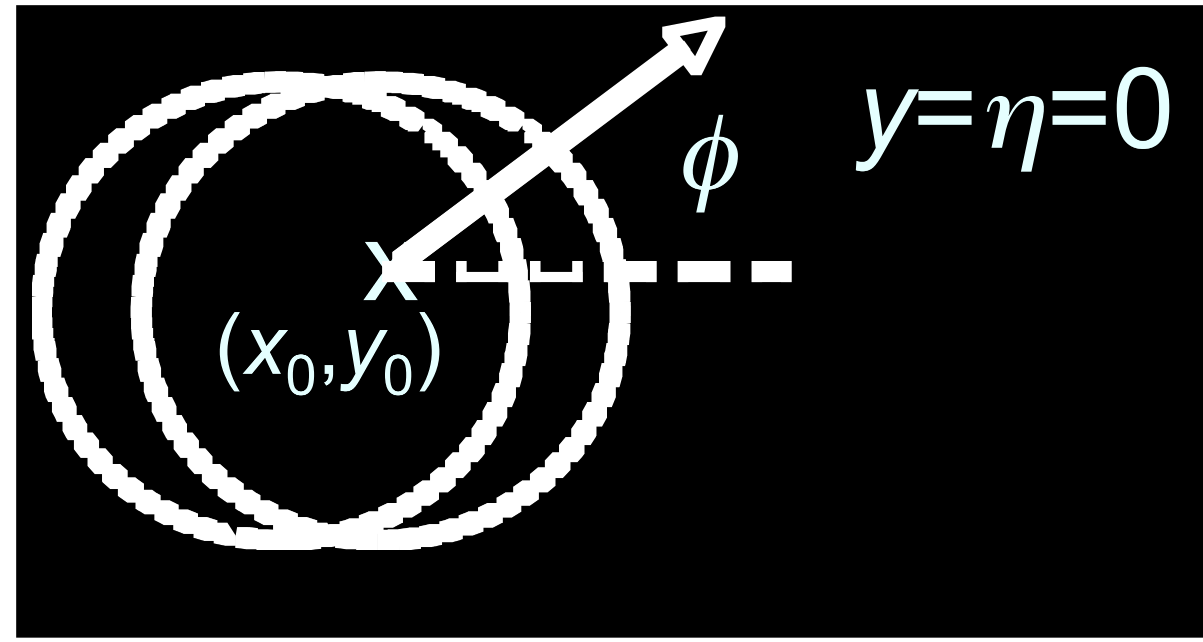
It does matter!!!

- Calculation of eloss has to be embedded in a geometry. Surface bias as an explanation of R_{AA}, tangential emission, p_T shape,...



   * Homogeneous piece of fixed length ⇒ qhat~1 GeV^2/fm.

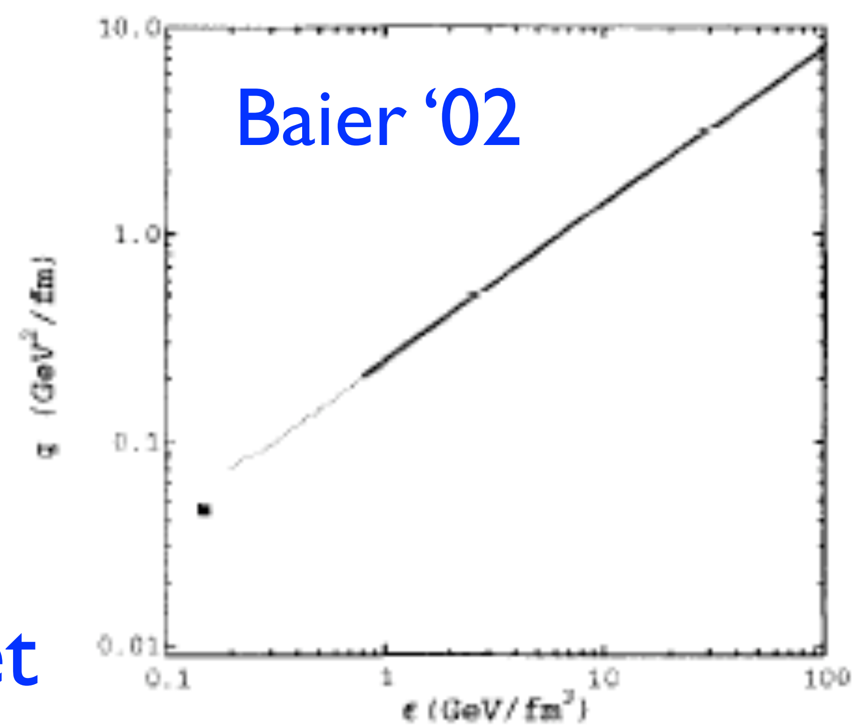
   * Density diluting as $1/\tau$ ⇒

   qhat~1 GeV^2/fm.

   * Medium as overlap (N_{coll}), $T_A(s)T_B(b\text{-}s)$ ⇒ qhat~10 GeV^2/fm.

   * Hydrodynamical medium ⇒ κ~2-4.

$$\hat{q}(\xi) = K\hat{q}_{\rm QGP} \simeq K \cdot 2e^{3/4}(\xi)$$

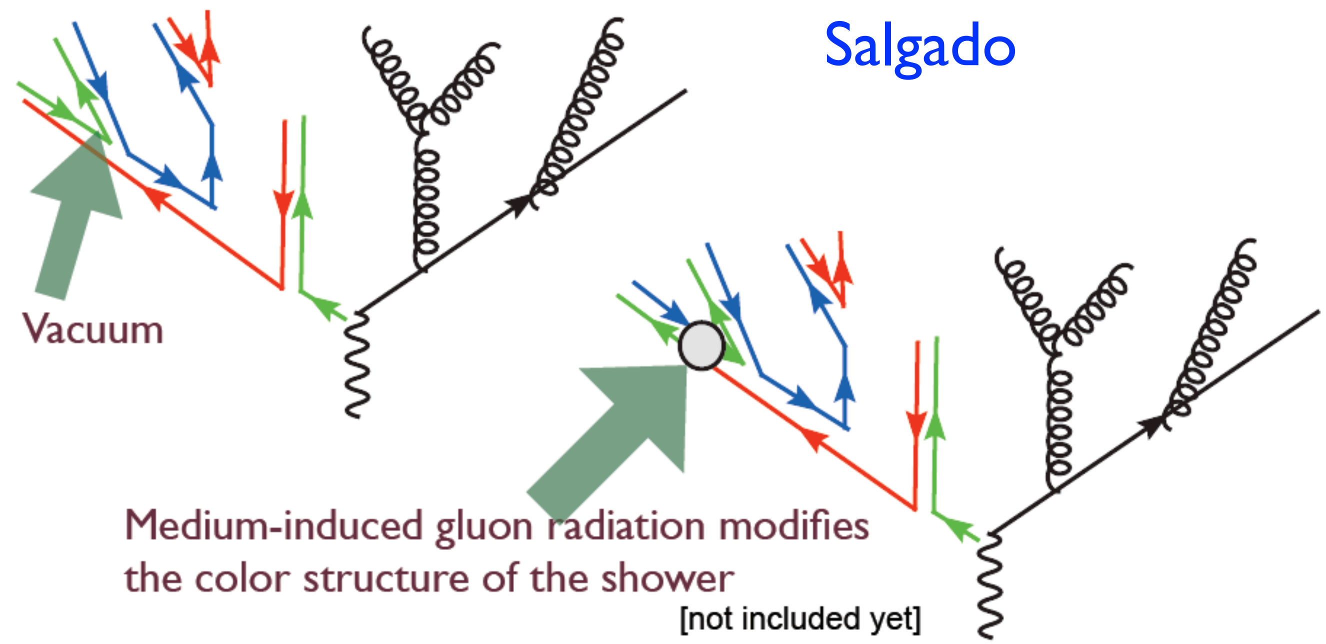


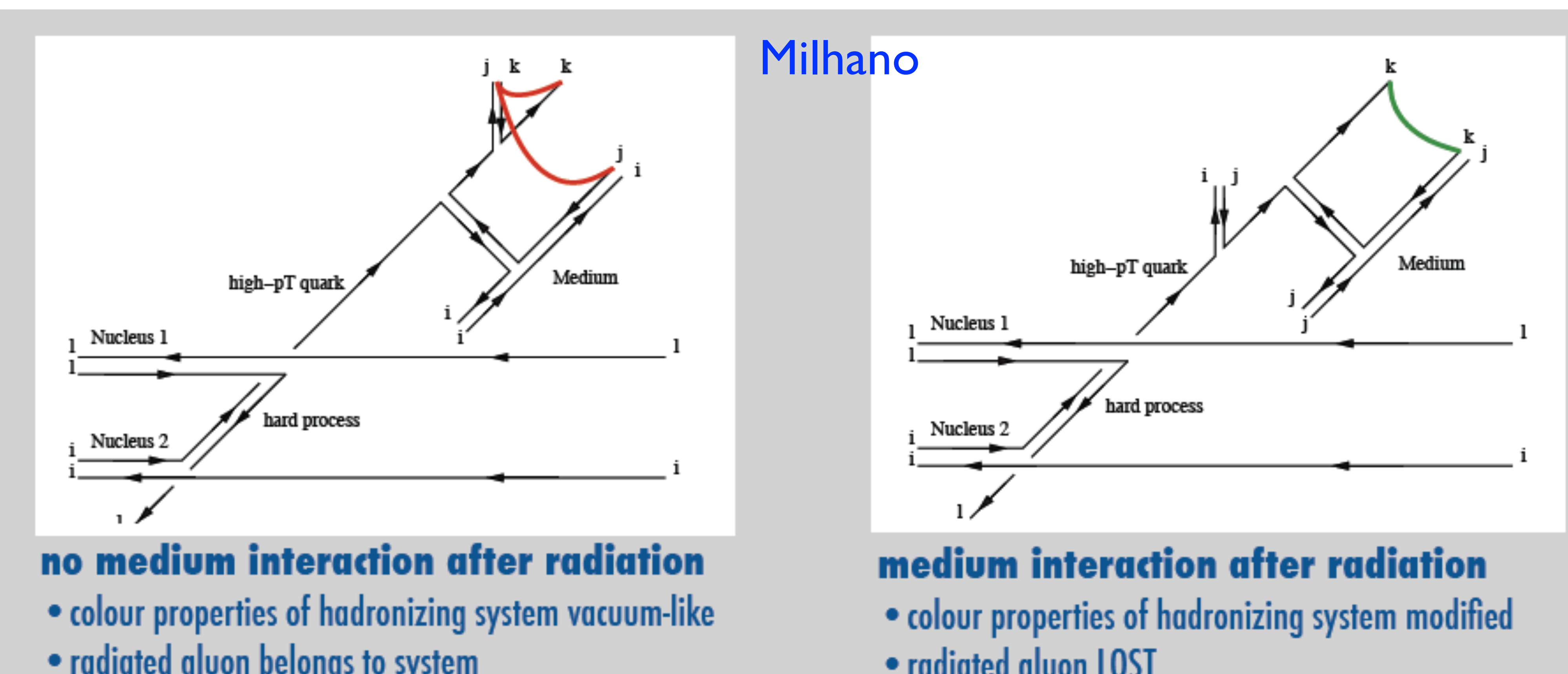
- At present: inclusion of flow, embedding in event-by-event viscous hydro (JET Coll.).

- Event-by-event sampling of medium (Fries et al) does not seem not results in large effects (Ko et al.).

Color reconnections:

- Medium transfers not only momentum: due to confinement, hadronization may become altered by changes of the color flow even for large p_T (where we used to think that hadronization was like in vacuum).





- Softeting of hadronic spectra (Beraudo et al '11).
- Change in hadrochemistry (Aurenche et al '11).

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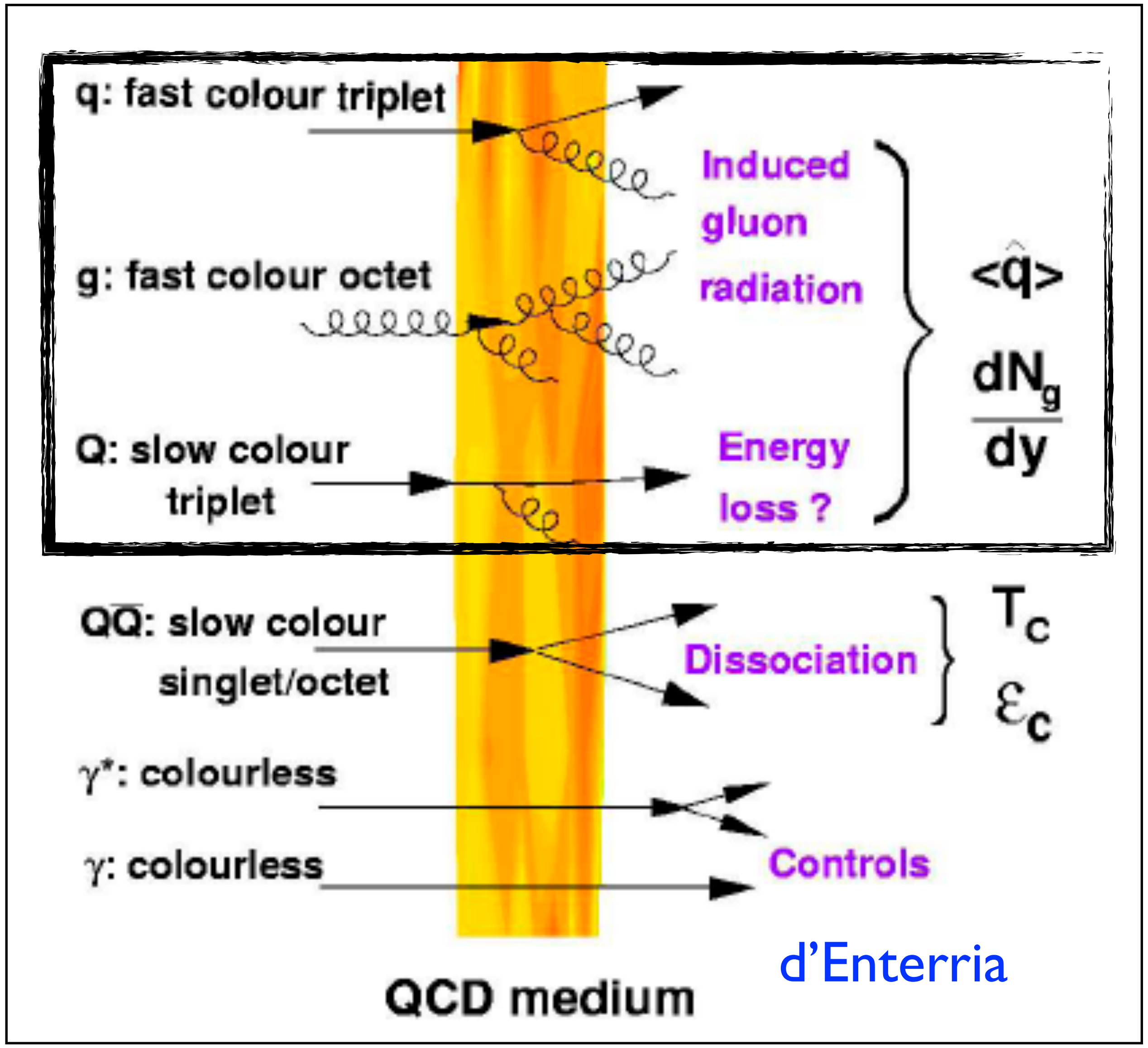
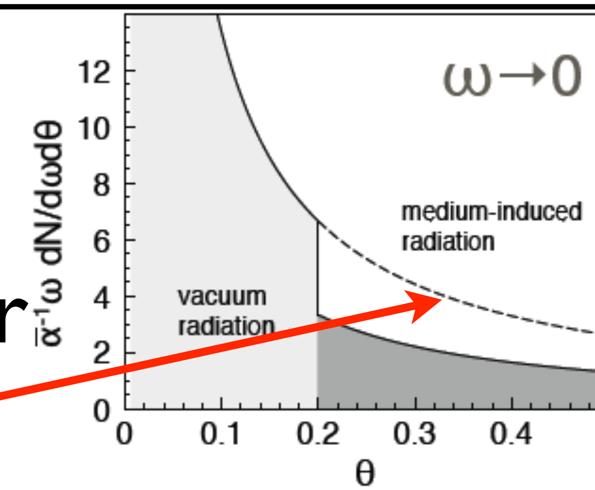
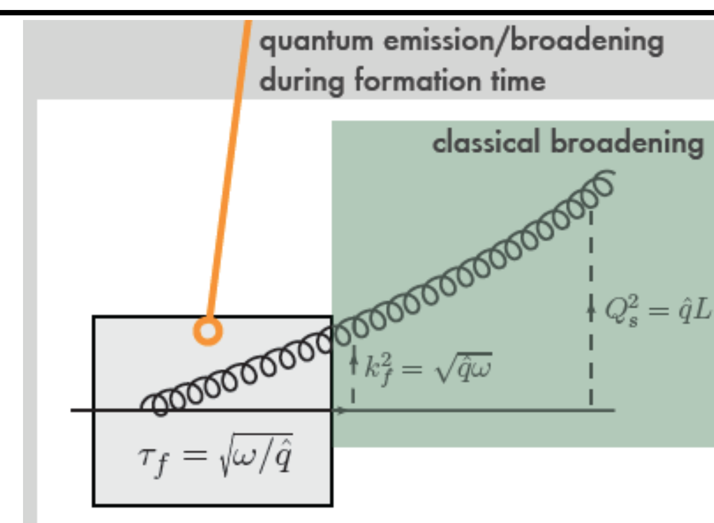
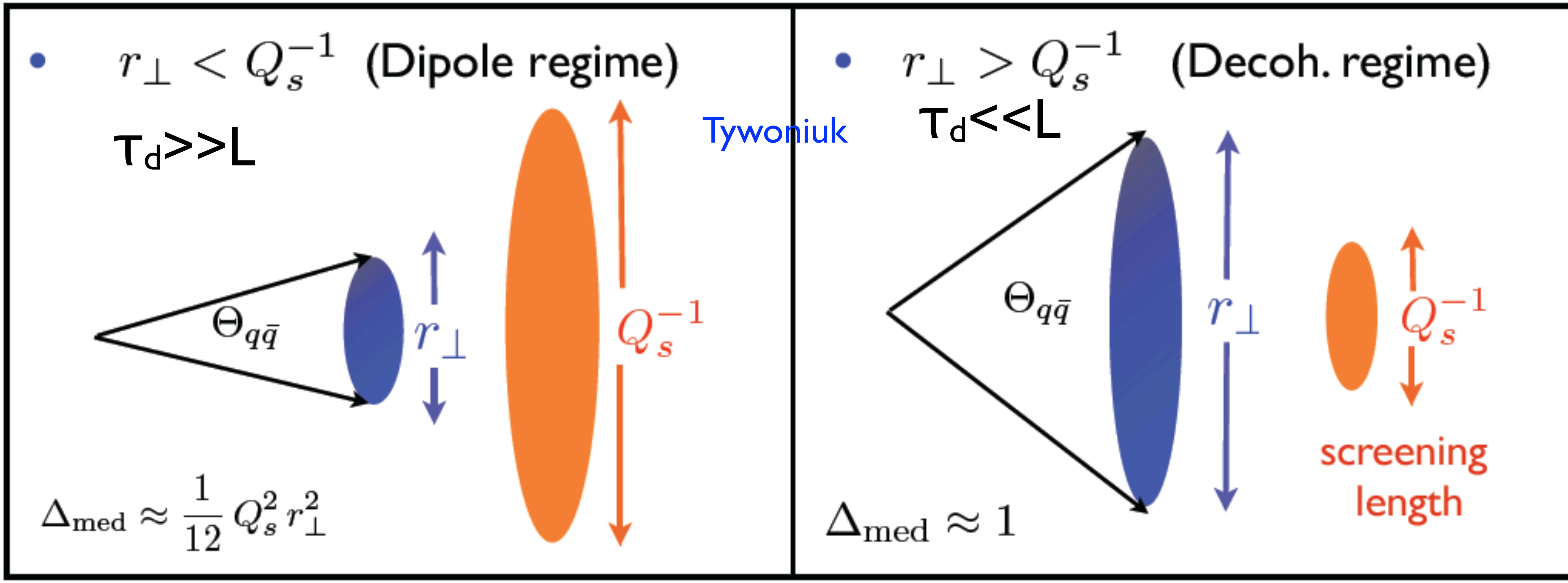


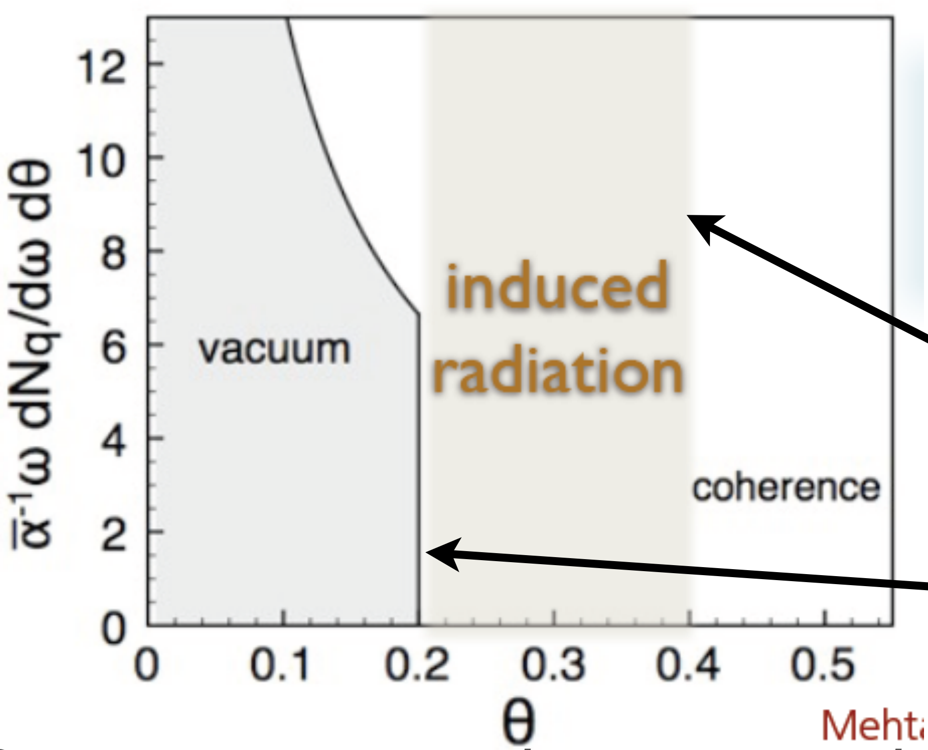
Coherence:

- Interference between emitters in a branching process as core of the probabilistic picture of the QCD cascade: ordering in angles → sequence emission kernel (DGLAP SF) × non-probability emission (Sudakov) ×... Basis of the Monte Carlo (PYTHIA, HERWIG, ...).
- In-medium jet calculus since 2010: Mehtar-Tani et al, Iancu et al.

	vacuum	medium
coherent	angular ordering, IR/ coll. divergent	anti-angular order for dilute medium (IR div.), independent emissions for dense: decoherence 
incoherent	IR/coll divergent	IR and coll. safe 

Scales:





$$1 - \Delta_{\rm med}(t,0) \simeq \exp\left[-\frac{1}{12}\hat{q}\theta_{q\bar{q}}^2 t^3\right] \Rightarrow \tau_d = \left(\hat{q}\theta_{q\bar{q}}^2\right)^{-1/3}$$

decoherence parameter

characteristic decoherence time

Q_{hard}/ω

θ_{qqbar}

Q_s^2=qhatL, $r_\perp = \theta_{q\bar{q}} L$

$Q_{hard}=\max(r_\perp^{-1}, Q_s, \omega\theta_{qqbar})$

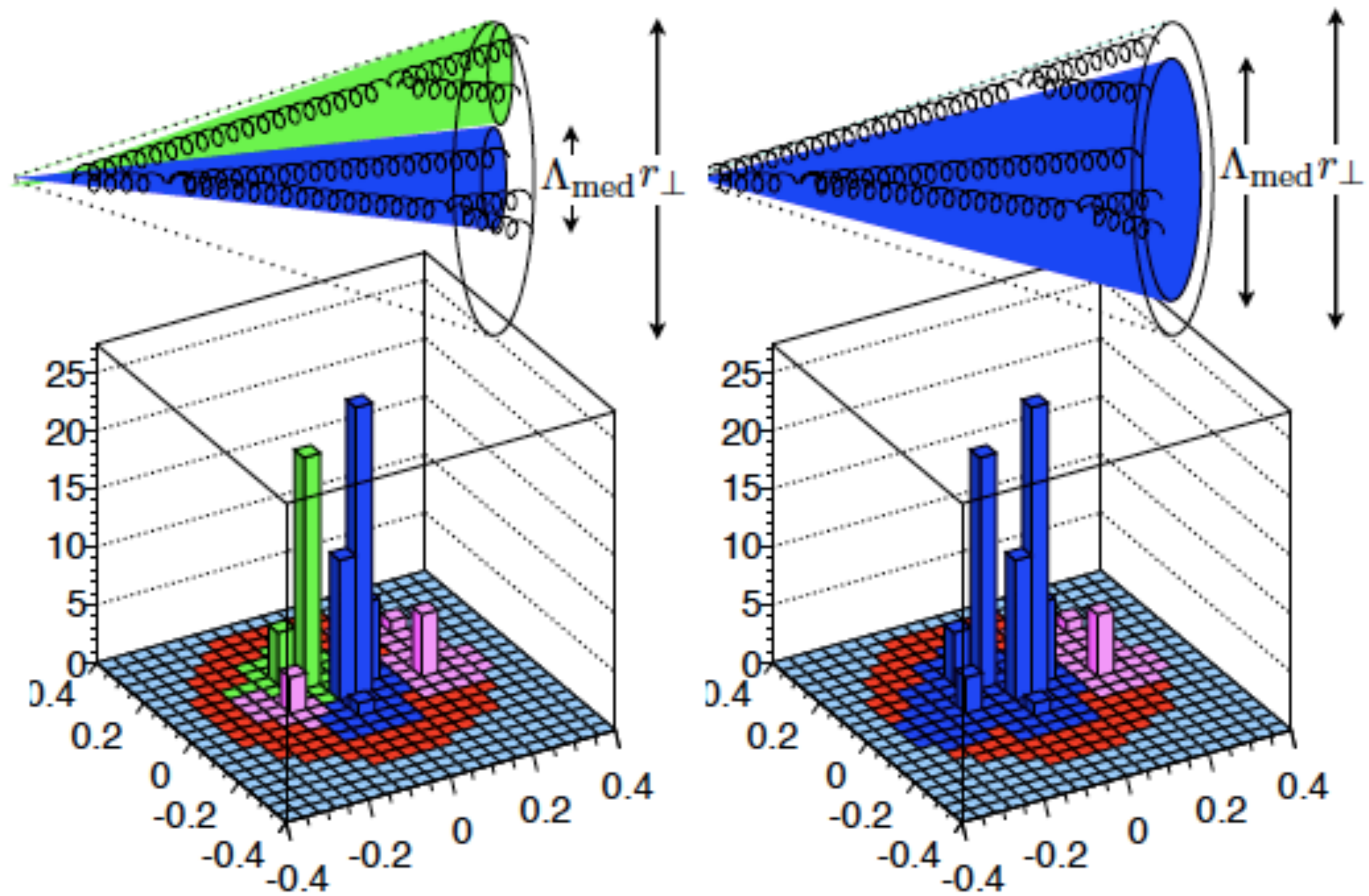
Implications:

- Blaizot et al '12: interferences suppressed by t_f/L. In the limit of small $t_f/L<<1$, probabilistic decohered branching process, in-medium splitting function, possible basis for Monte Carlo.

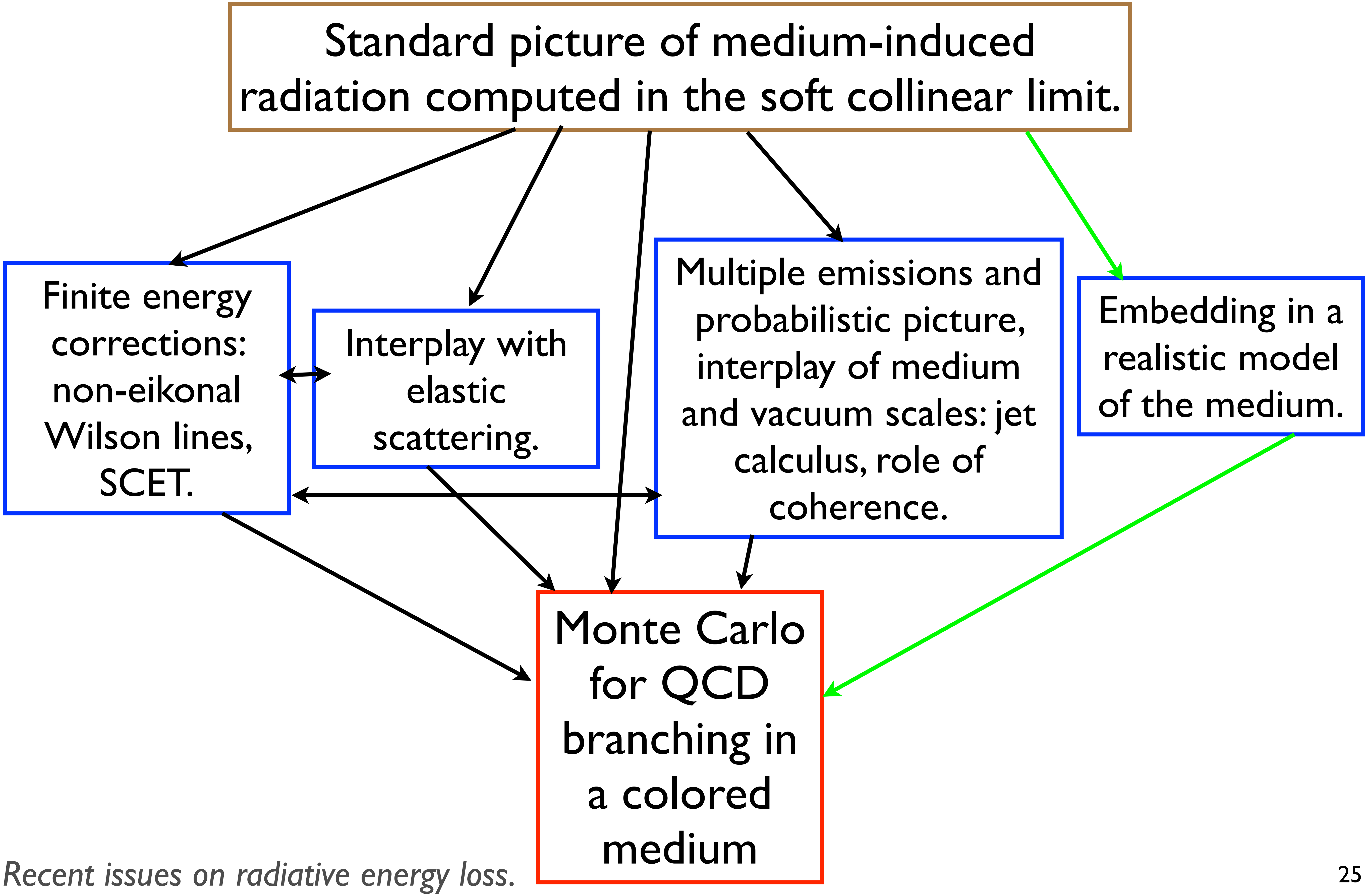
- Casalderrey et al '12: jet resolution scale, that leads to:
  - ➜ $\Theta=\Theta_{jet}<\theta_c$: unresolved jet constituents, fragment as in vacuum, no medium effect for $z>Q_0/E\theta_c$.
  - ➜ $\Theta=\Theta_{jet}>\theta_c$: jet constituents resolved, soft decohered radiation at large angles.

$$\Delta_{\rm med} \simeq 1 - e^{-\frac{1}{12}\hat{q}Lr_\perp^2} \equiv 1 - e^{-(\Theta/\theta_c)^2}$$

$r_\perp=\Theta L$, $\theta_c=\sqrt{12/\hat{q}L^3}$, $\Lambda_{med}=1/\sqrt{\hat{q}L}$



Summary:


Standard picture of medium-induced radiation computed in the soft collinear limit.
Finite energy corrections: non-eikonal Wilson lines, SCET.
Interplay with elastic scattering.
Multiple emissions and probabilistic picture, interplay of medium and vacuum scales: jet calculus, role of coherence.
Embedding in a realistic model of the medium.
Monte Carlo for QCD branching in a colored medium

Summary:

- Energy loss in QCD is a very interesting subject!!!:
  ➜ Calculation of QCD radiation in a medium: link between weak and strong coupling, relations with high-energy QCD, with effective theory techniques, with resummations, questions on factorisation,...
  ➜ A precise understanding of the mechanisms of energy loss is required for any accuracy in characterizing the dense medium produced in high-energy heavy-ion collisions.

- Not mentioned here: jet reconstruction in a large background (Cacciari et al, Apolinario et al), NLO corrections, eloss in Glasma, AdS/CFT issues, qhat in lattice, weak versus strong coupling,...

branching in
a colored
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  ➜ Calculation of QCD radiation in a medium: link between weak and strong coupling, relations with high-energy QCD, with effectiv[…] […]ons on factoris[…]
  ➜ A pr[…] […]gy loss is require[…] […]medium produc[…]

Thanks to you all for your attention!!!

Thanks to Alejandro and the organizers for the invitation!!!

Many congratulations to Guy!!!!!

- Not men[…] […]round (Cacciari et al, Apolinario et al), NLO corrections, eloss in Glasma, AdS/CFT issues, qhat in lattice, weak versus strong coupling,...

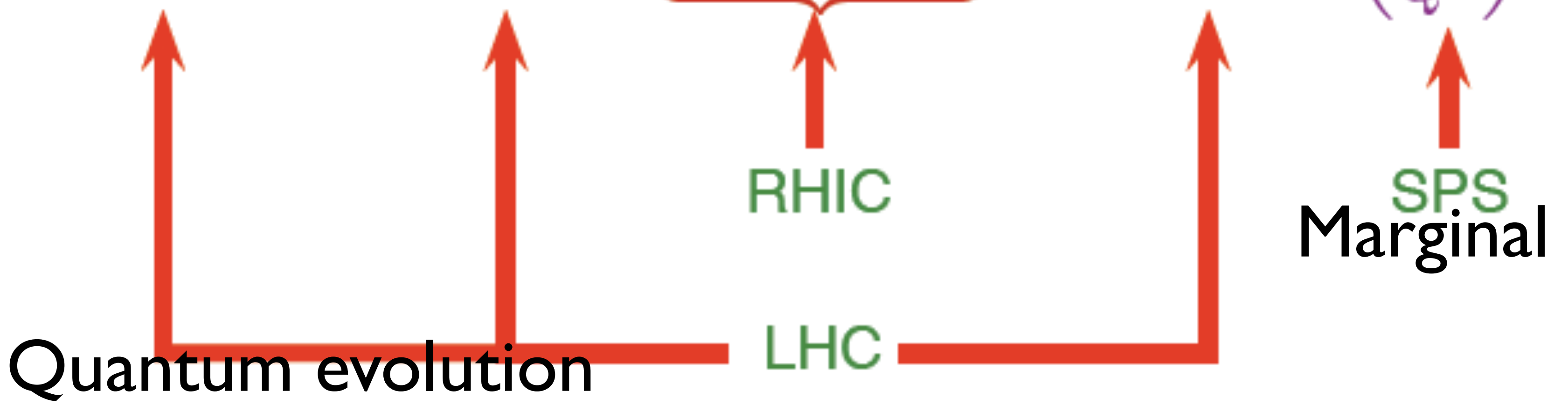
[…] QCD branching in a colored medium

Backup:

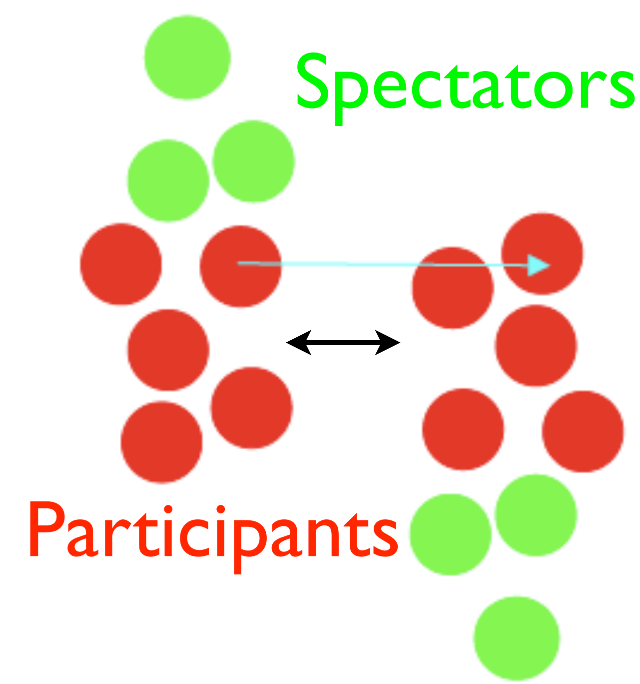
Factorization:

- The usual tool to compute particle production is collinear factorization (for $Q \sim E_{cm} \gg \Lambda_{QCD}$):

$$\sigma^{pp\to h} = f_p(x_1,Q^2) \otimes f_p(x_2,Q^2) \otimes \sigma(x_1,x_2,Q^2) \otimes D(z,Q^2) + \left(\frac{1}{Q^2}\right)^n$$



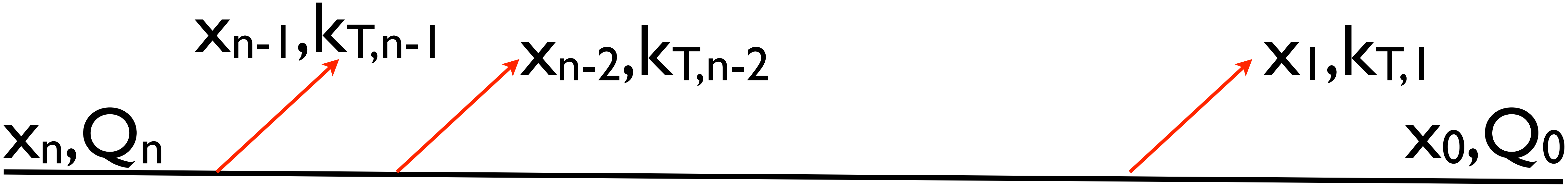
- Nuclear corrections - no medium, QGP or not - to parton densities and fragmentation functions poorly known.



- Nuclear effects usually discussed through the ratio measured/expected: nuclear modification factor, =1 in absence of nuclear effects.

$$R^k_{AB}(y,p_T) = \frac{\frac{dN^k_{AB}}{dy dp_T}}{\langle N_{coll}\rangle \frac{dN^k_{pp}}{dy dp_T}}$$

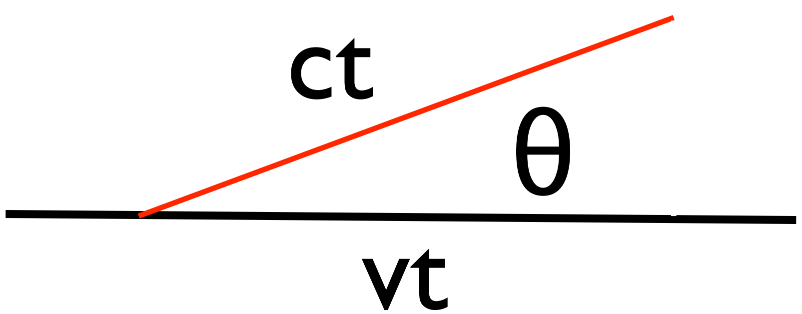
Radiation: dead cone, ang. ordering



$$dP_i = \frac{dx_i}{x_i}\frac{dk_{T,i}^2}{k_{T,i}^2}, \quad \omega_i = x_i E, \quad \theta_i^2 \simeq \frac{k_{T,i}^2}{\omega_i^2}$$

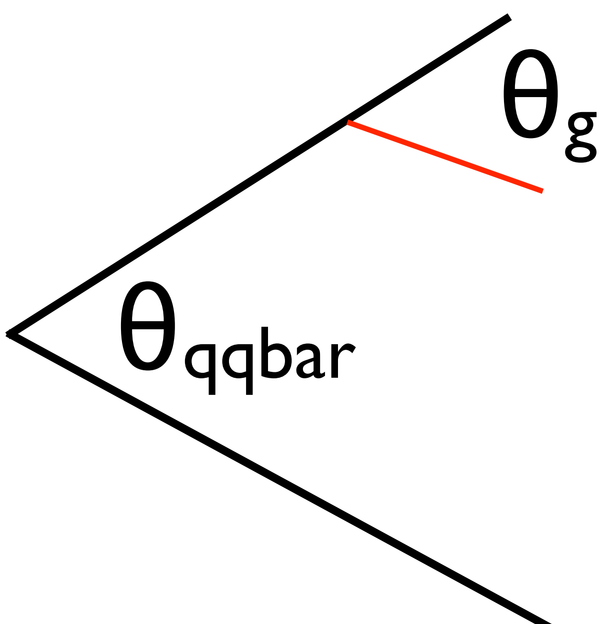
$$Q_n^2 \gg k_{T,n-1}^2 \gg k_{T,n-2}^2 \gg \ldots \gg k_{T,1}^2 \gg Q_0^2$$

$$x_n \ll x_{n-1} \ll x_{n-2} \ll \ldots \ll x_1 \ll x_0$$



$$vt \simeq ct(1-\theta_0^2) \Rightarrow \theta_0^2 = m^2/E^2, \quad \theta^2 \to \theta^2 + \theta_0^2$$

Infrared (soft) and collinear (mass) divergencies.



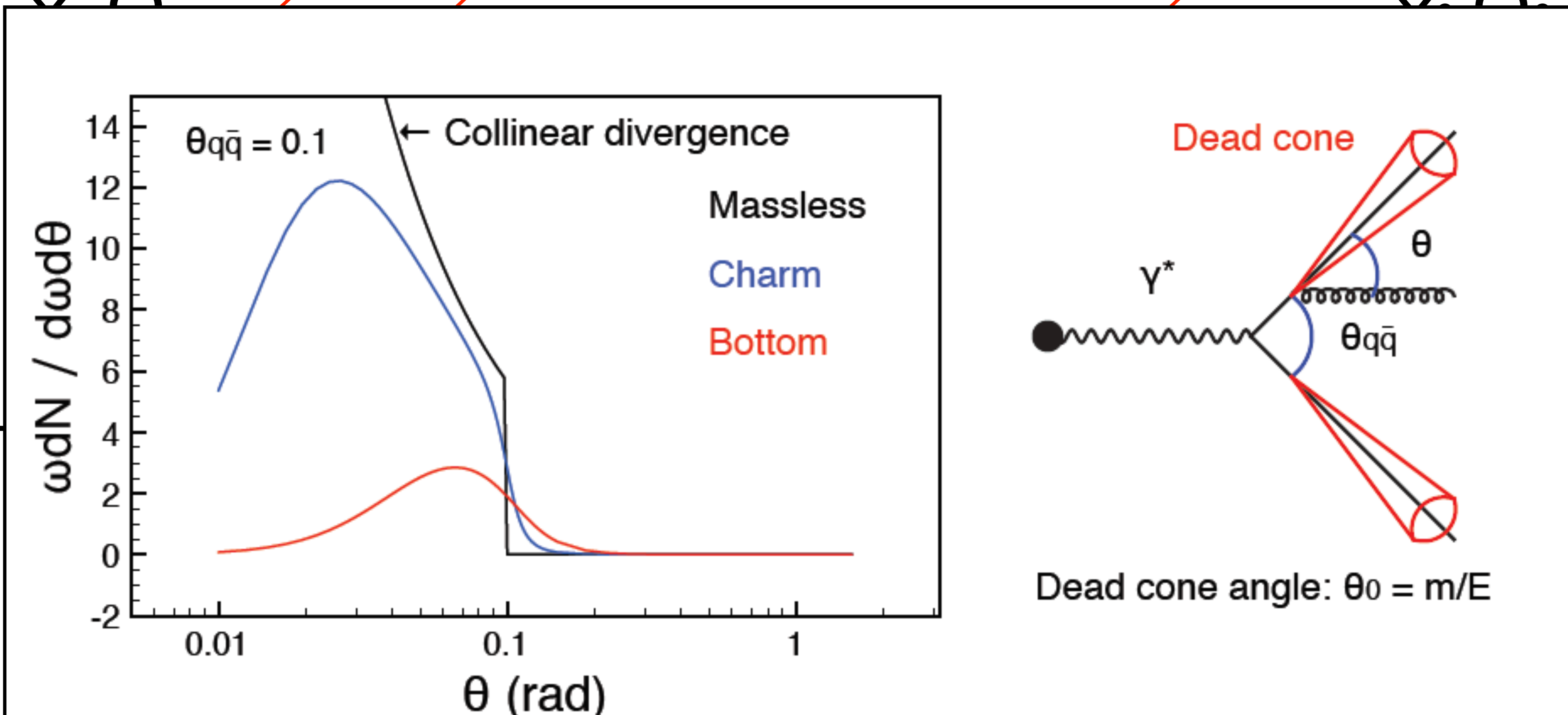
Angular ordering: |qqbarg> → |qqbar>+|g>

$$D_{q\bar{q}} = \theta_{q\bar{q}} t_{coh}, \quad t_{coh} \sim \omega/k_T^2, \quad D_g \sim 1/k_T$$

$$D_{q\bar{q}} = \frac{\theta_{q\bar{q}}}{k_T \theta_g} > D_g \Rightarrow \theta_g < \theta_{q\bar{q}}$$

Radiation: dead cone, ang. ordering

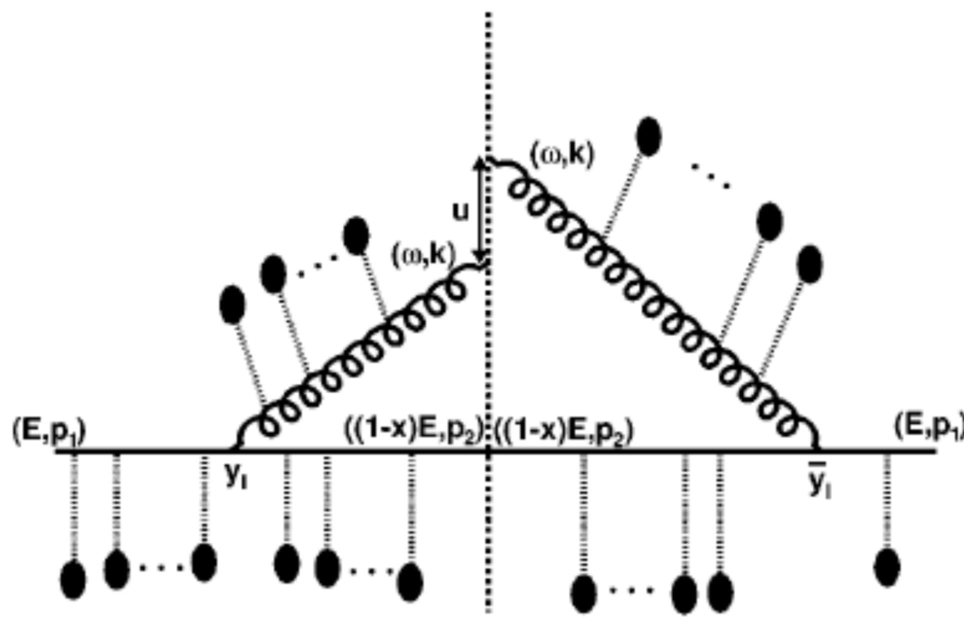
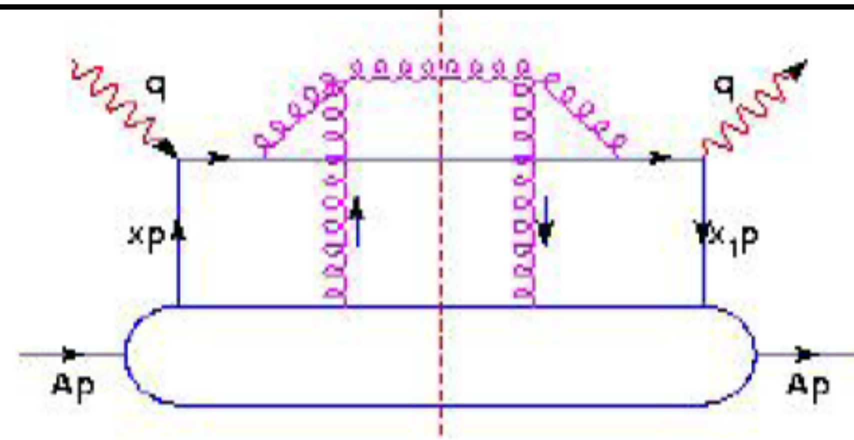
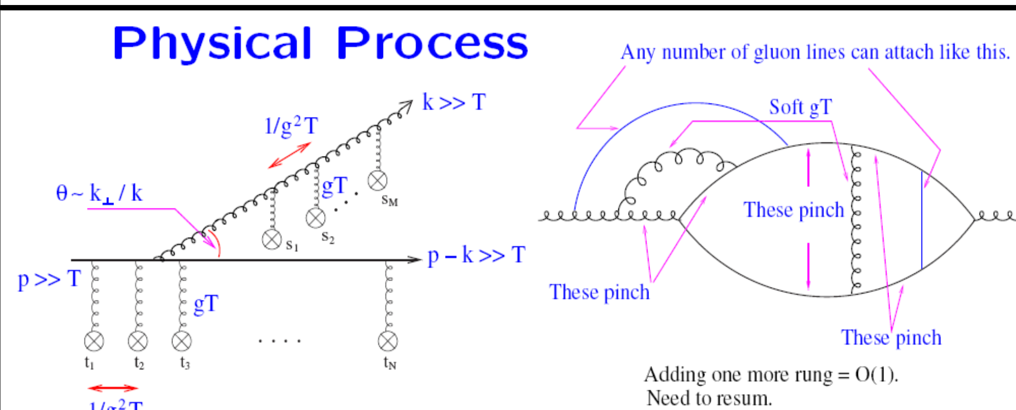
$x_{n-1}, k_{T,n-1}$ $x_{n-2}, k_{T,n-2}$ $x_1, k_{T,1}$



θ_{qqbar}

$$D_{q\bar{q}} = \frac{\theta_{q\bar{q}}}{k_T \theta_g} > D_g \Rightarrow \theta_g < \theta_{q\bar{q}}$$

Model list:

<table>
<tr><th>Model</th><th>Diagrams</th><th>Ingredients</th><th>Parameter</th></tr>
<tr><td>ASW</td><td rowspan="2">
</td><td rowspan="2">Static scattering centers, Poissonian QW</td><td>qhat</td></tr>
<tr><td>GLV / WHDG(elastic)</td><td>$dN_g/dy, T$ / α_s, T</td></tr>
<tr><td>GMW</td><td>
</td><td>FF in eA, modified DGLAP</td><td><FF> or qhat, T</td></tr>
<tr><td>AMY (elastic)</td><td>
</td><td>HTL medium, rate eqs.</td><td>α_s, T</td></tr>
</table>

Radiative eloss: limitations

- The extracted value of qhat depends on medium model $1 < \hat{q} < 15$ GeV^2/fm ⇒ interface with realistic medium.

- Calculat ... ly soft emissions ... steriori ⇒ Monte Ca

$$\omega \frac{dI}{d\omega} = \int_0^{k_T^{2,max}} dk_T^2\, \omega \frac{dI}{d\omega dk_T^2}\,, \quad \Delta E = \int_0^E d\omega\, \omega \frac{dI}{d\omega}$$

$$P(\Delta E) = \omega \frac{dI}{d\omega} = \int_0^{k_T^{2,max}} dk_T^2\, \omega \frac{dI}{d\omega dk_T^2}\,, \quad \Delta E = \int_0^E d\omega\, \omega \frac{dI}{d\omega}$$

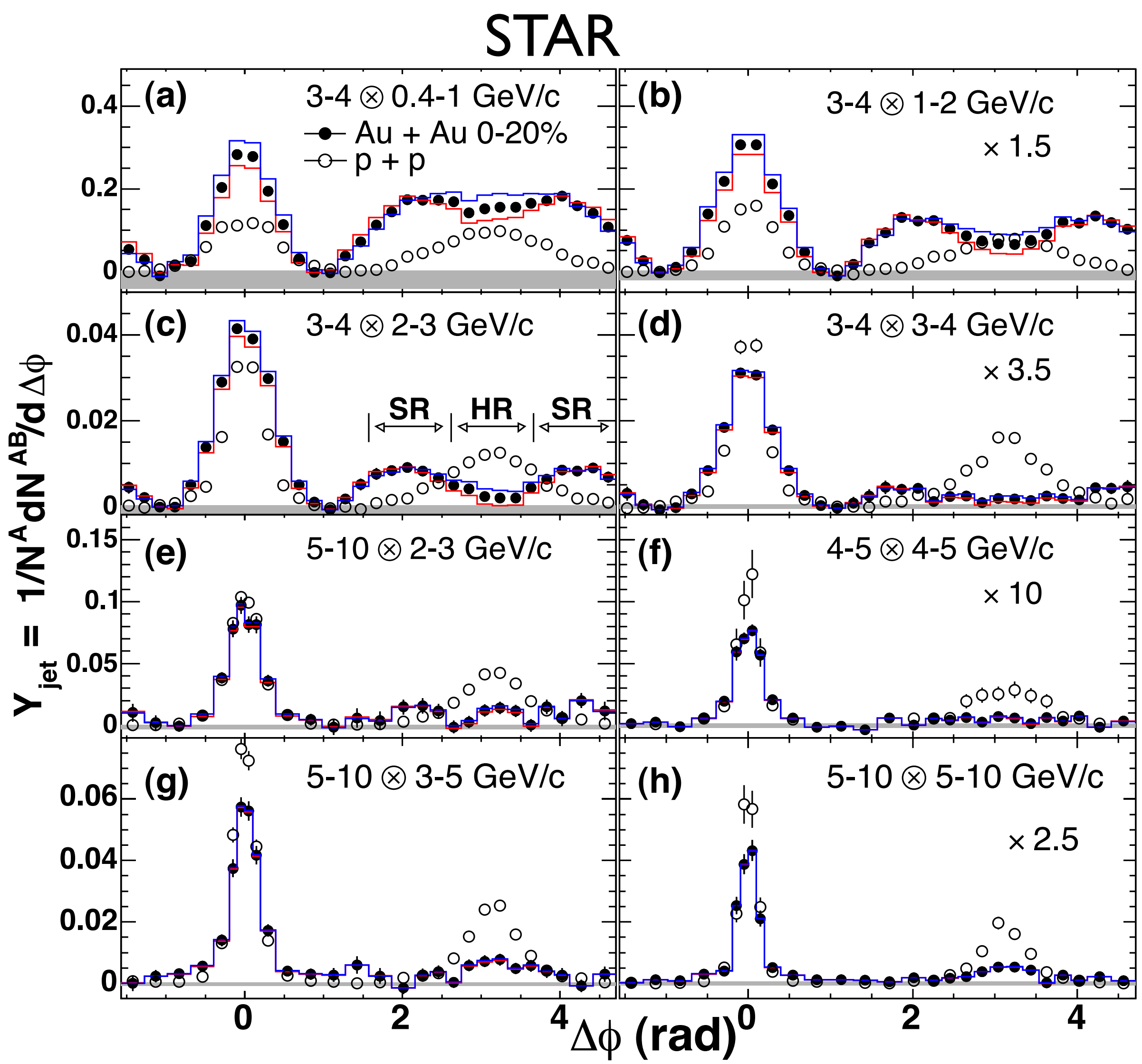
- Multip'- ... nt (Poisson ... PQM, PYQU

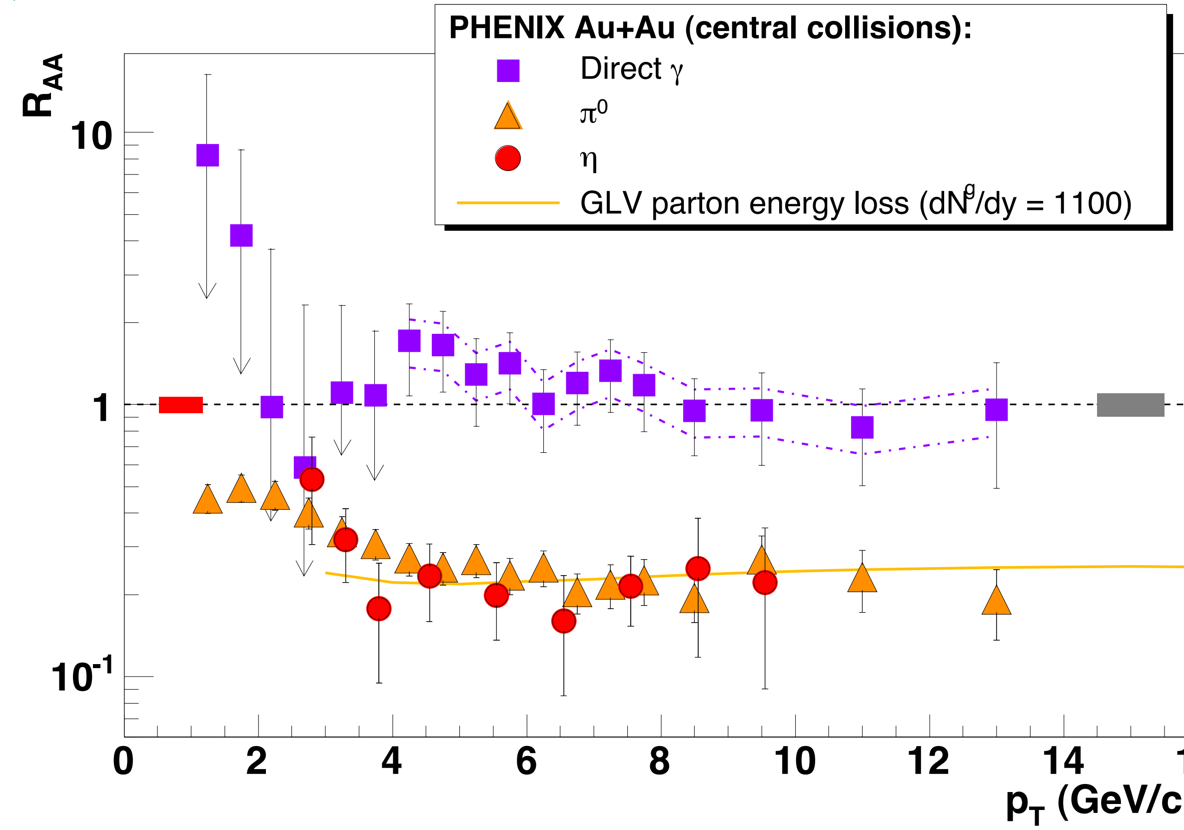
$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i \right) \exp\left[- \int d\omega \frac{dI}{d\omega} \right]$$

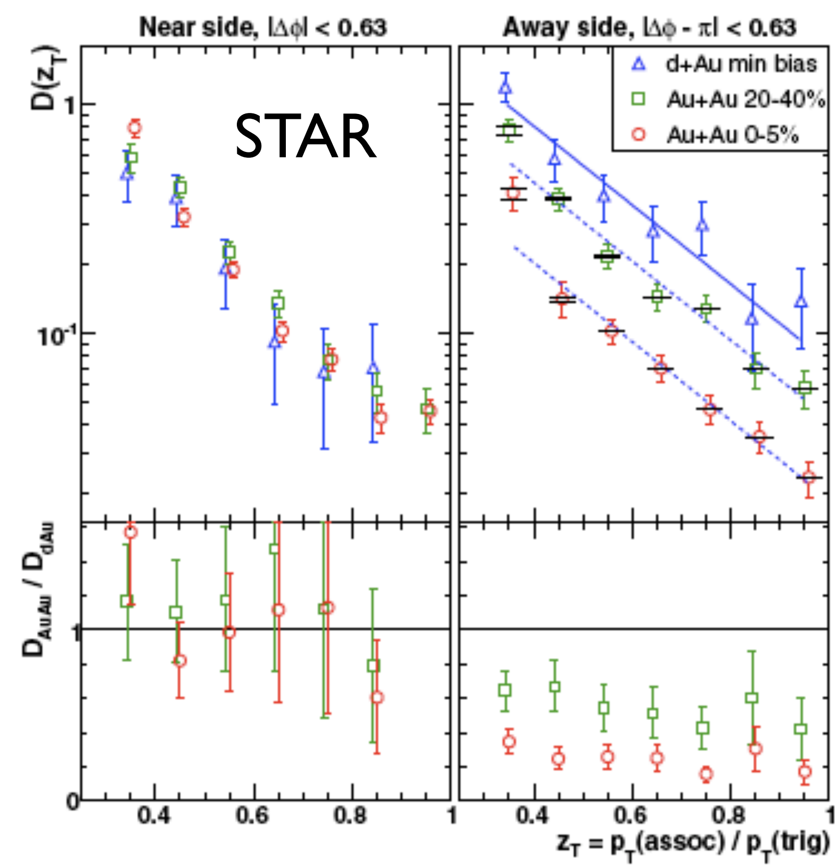
$$P_{trunc}(\Delta E) = p_0 \delta(\Delta E) + P_{cont}(\Delta E)\Theta(E - \Delta E) + \delta(E - \Delta E) \int_E^{\infty} d\epsilon P(\epsilon)$$

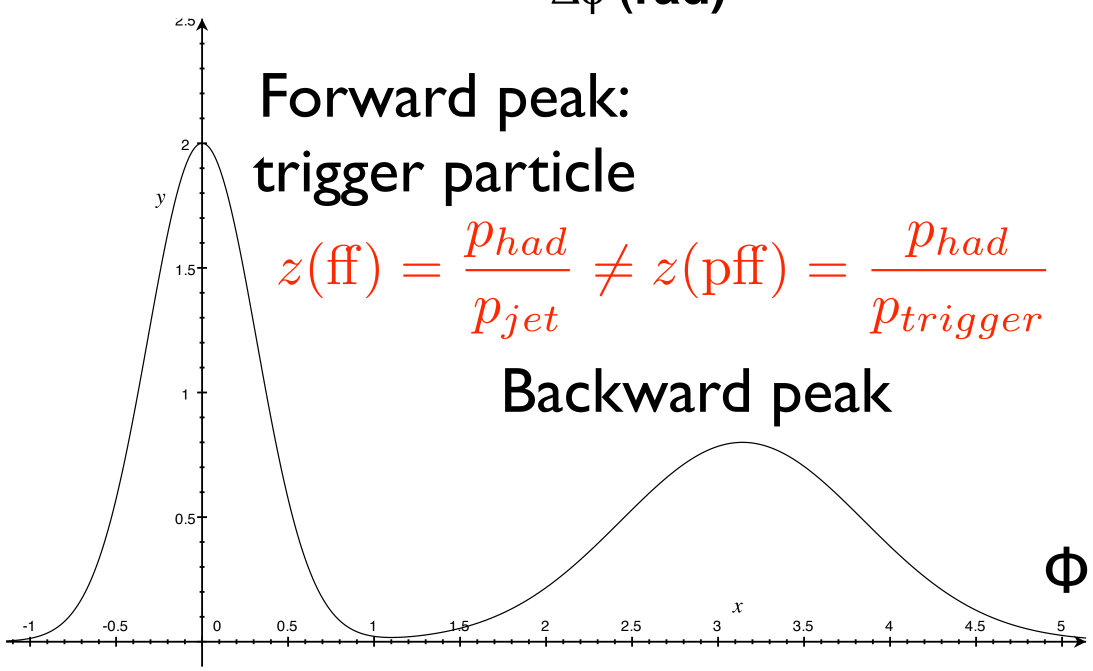
- No role of virtuality in medium emissions, medium and vacuum treated differently ⇒ modified DGLAP evolution.

Radiative eloss: light hadrons (I)









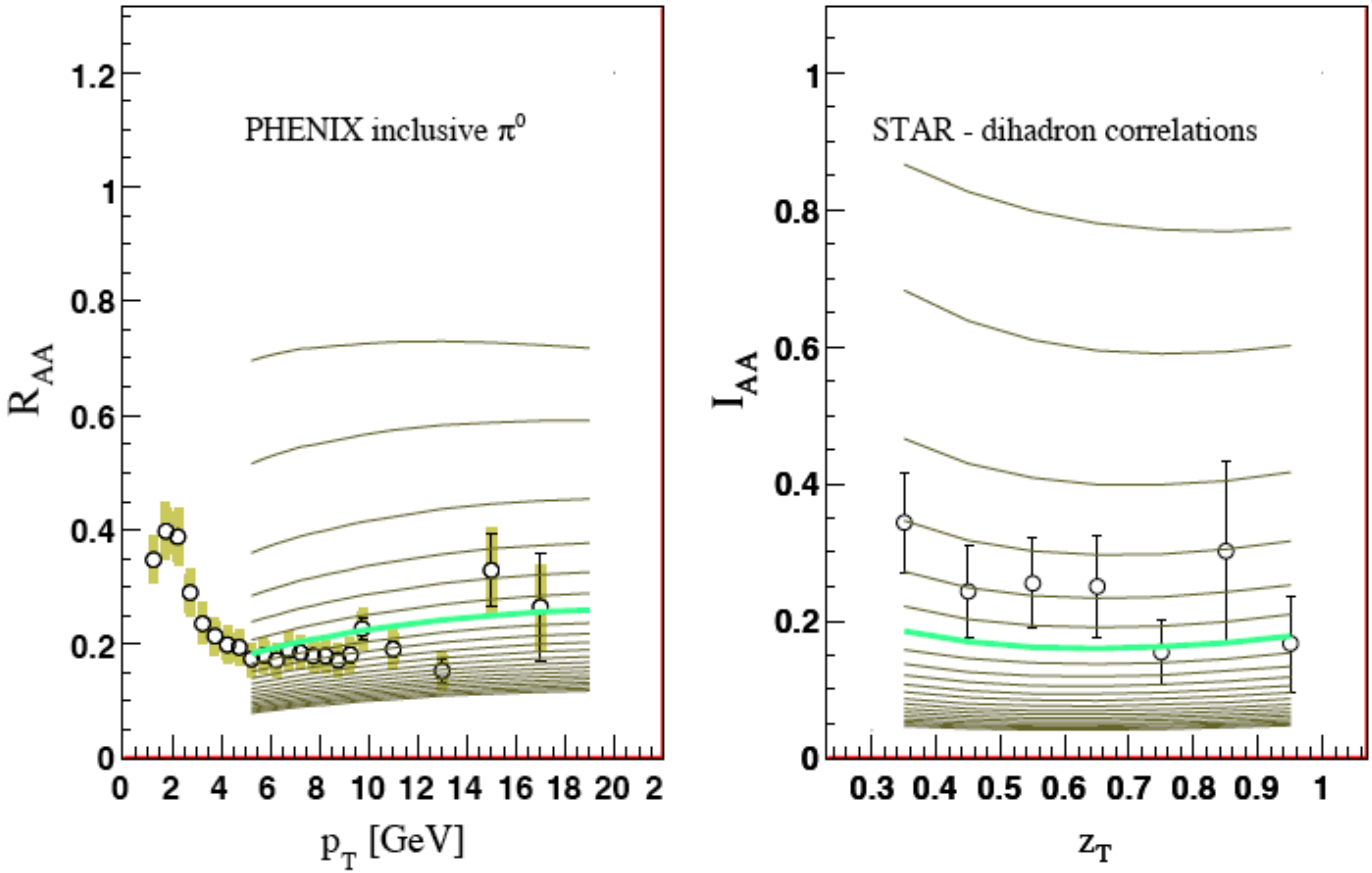
Forward peak: trigger particle

$$z(\text{ff}) = \frac{p_{had}}{p_{jet}} \neq z(\text{pff}) = \frac{p_{had}}{p_{trigger}}$$

Backward peak

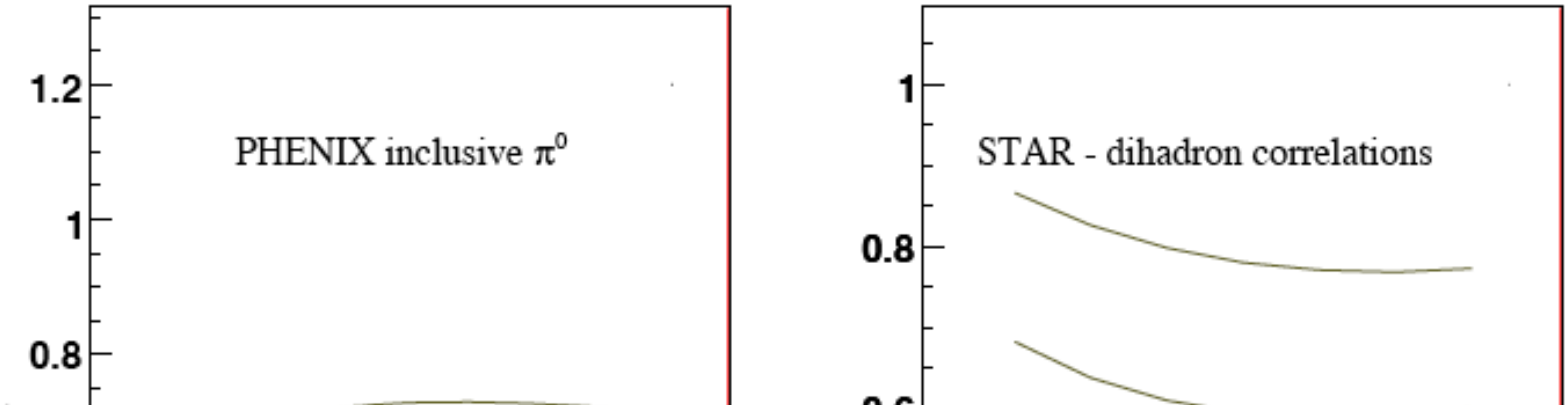
Radiative eloss: light hadrons (II)

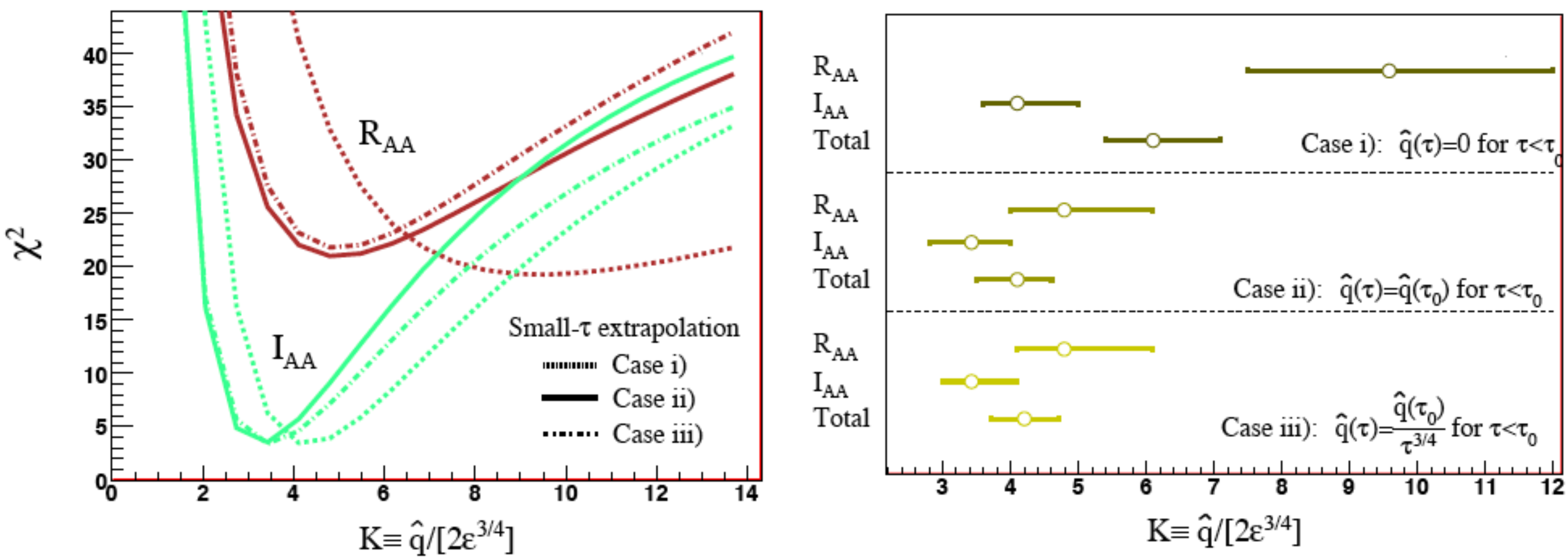
NA et al '09



Radiative eloss: light hadrons (II)

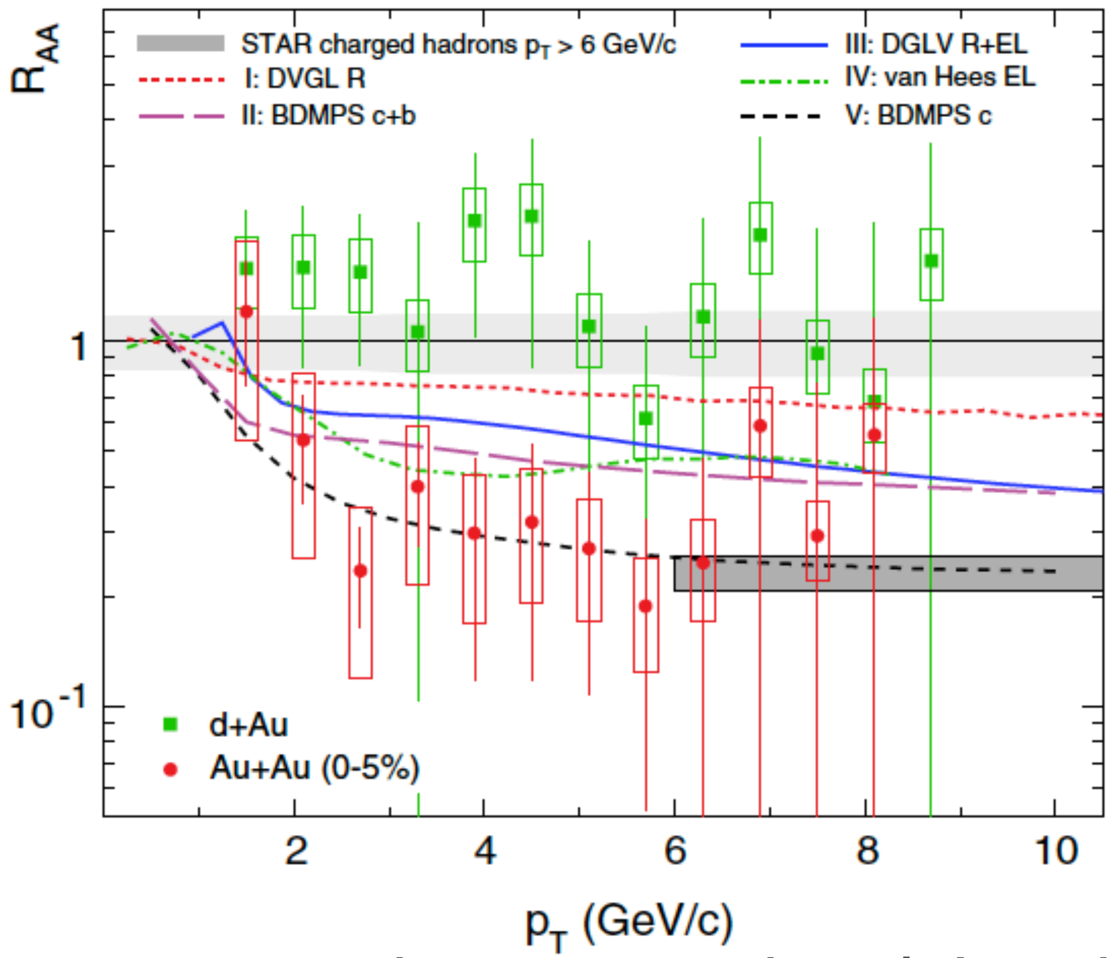
NA et al '09

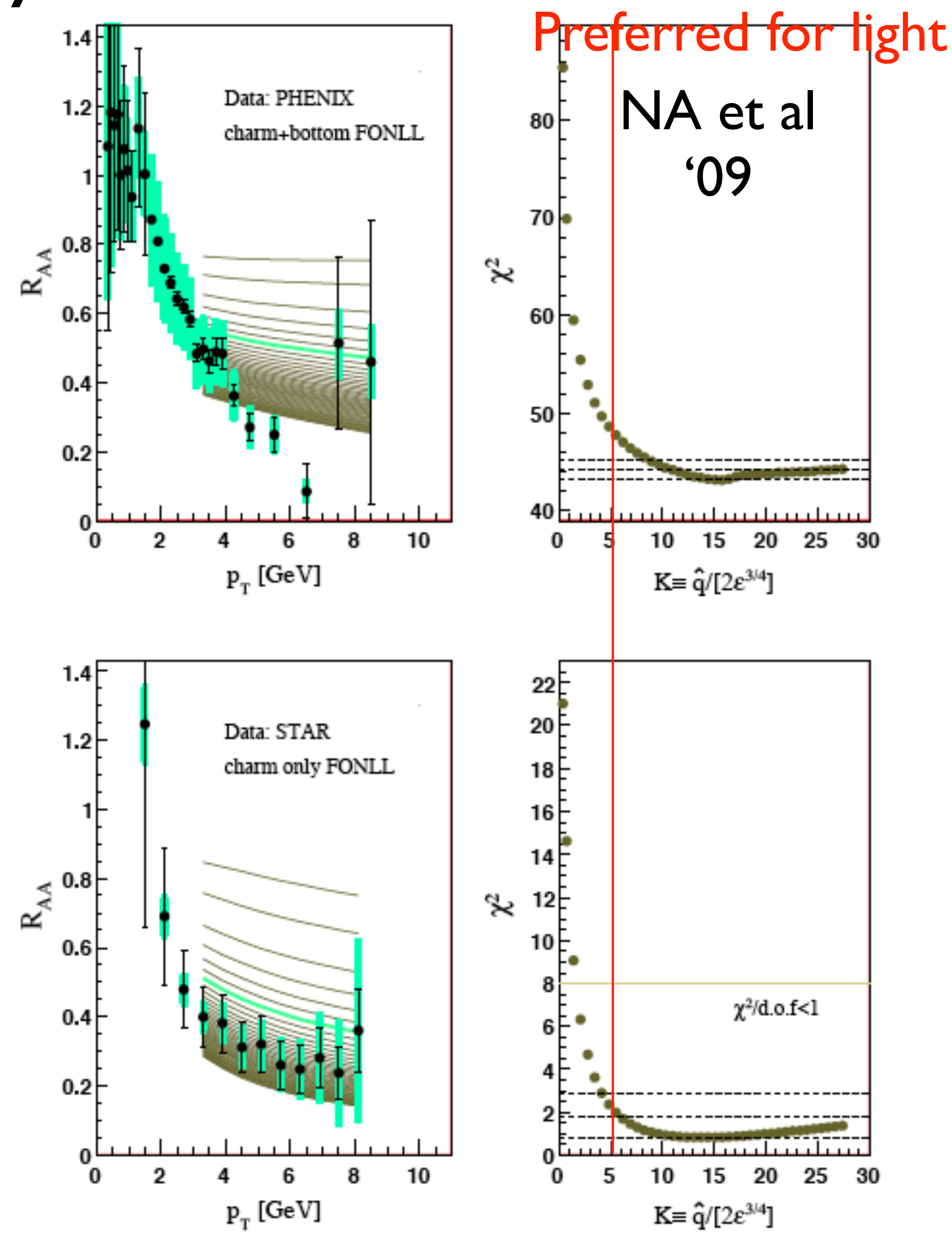




Radiative eloss: non-photonic e's

- Prediction from radiative energy loss: **ΔE(g)>ΔE(q)>ΔE(Q)**.
- Non-photonic electrons not conclusive: benchmark, hadronization, collisional, resonances dynamical medium ...
- Very difficult observable: disentangle c, b, heavy mesons,...





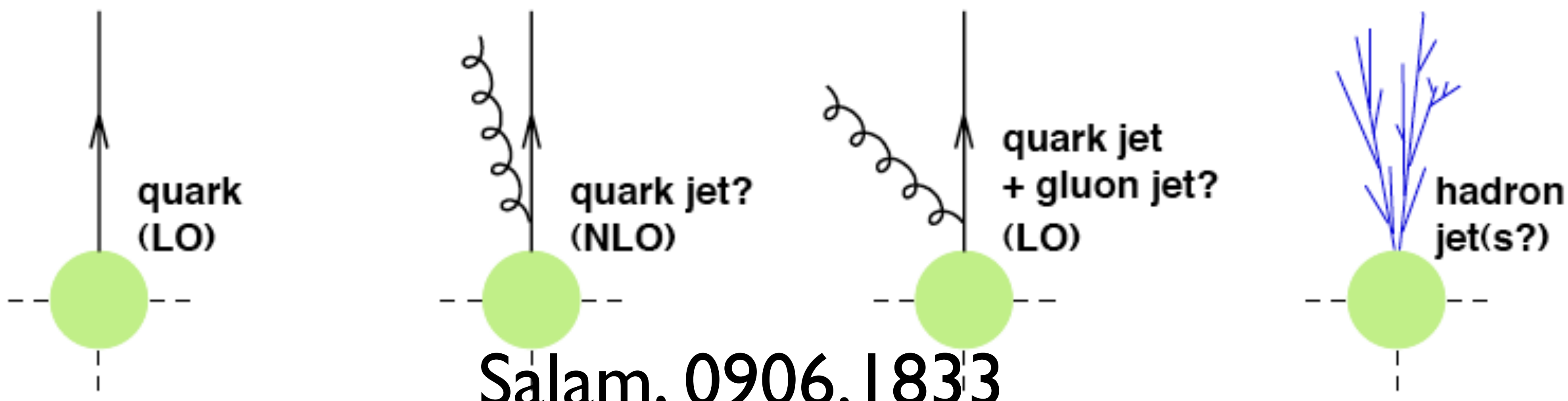
Jets (I):

- Single-particle inclusive distributions suffer from several biases: steep partonic spectrum which enhances small energy losses (trigger bias), geometric bias towards the surface,...

- They come from our inability to reconstruct the energy of the 'parton': we cannot distinguish a low energy, little degraded one from a high energy, highly degraded one.

Jets are the most direct of all hard probes of the medium.

As close as you can get to the original quark or gluon near its time of creation



Salam, 0906.1833

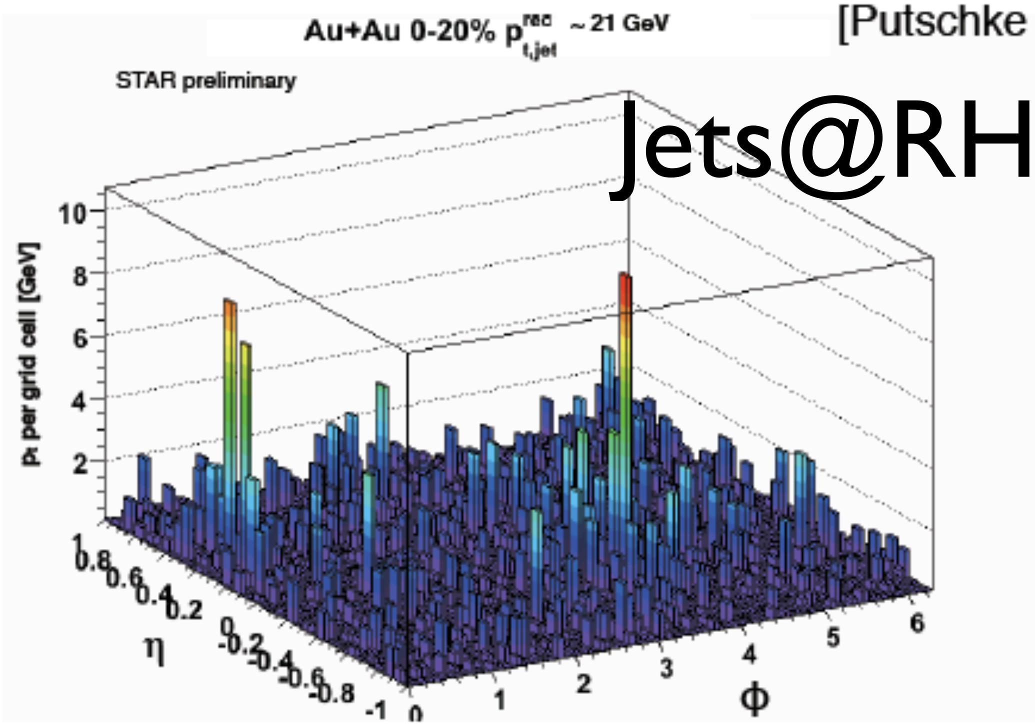
- Jets come with a definition: clustering or reconstruction algorithm.

Jets (I):

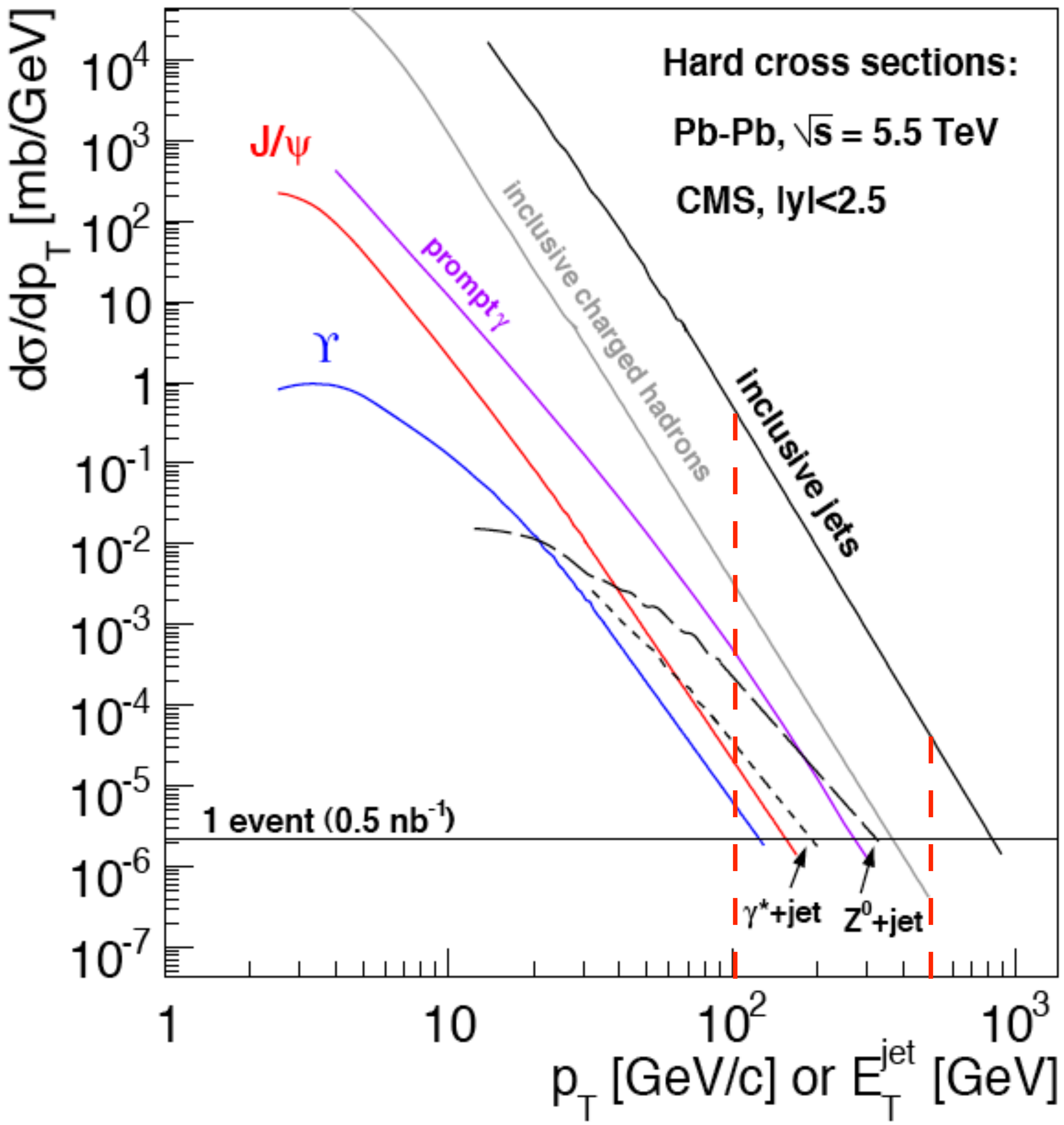
- Single-particle inclusive distribut
steep partonic spectrum which en
(trigger bias), geometric bias towa

First results appeared in HP2008!

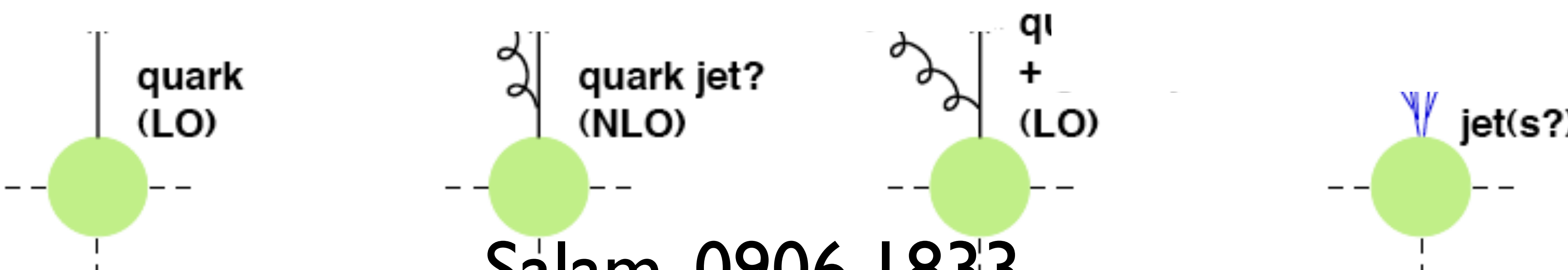
[Putschke HP08]



Jets@RHIC



A lot of work still needed

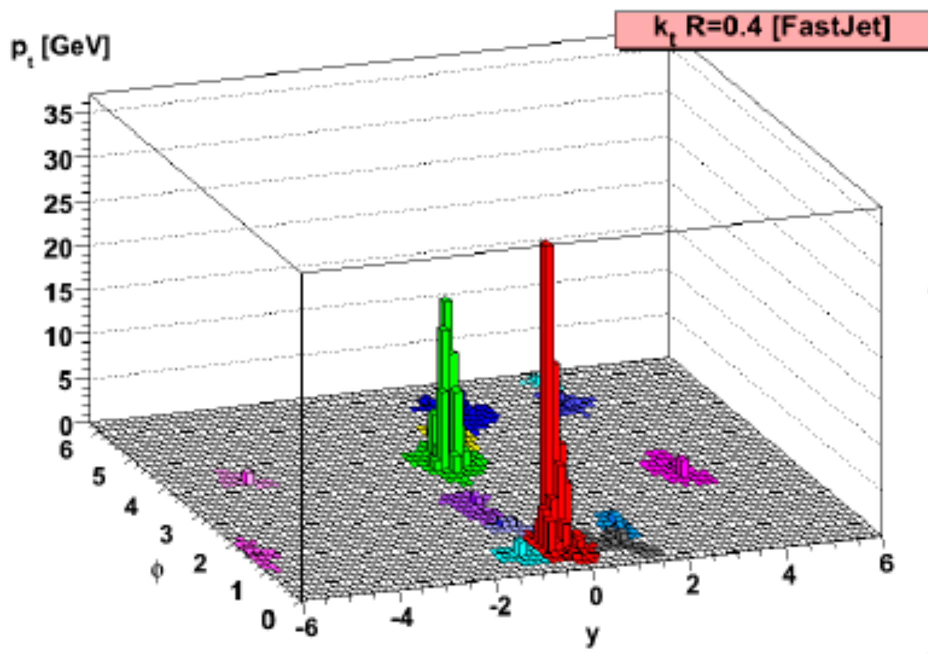


Salam, 0906.1833

clustering or reconstruction algorithm.

Jets (II):

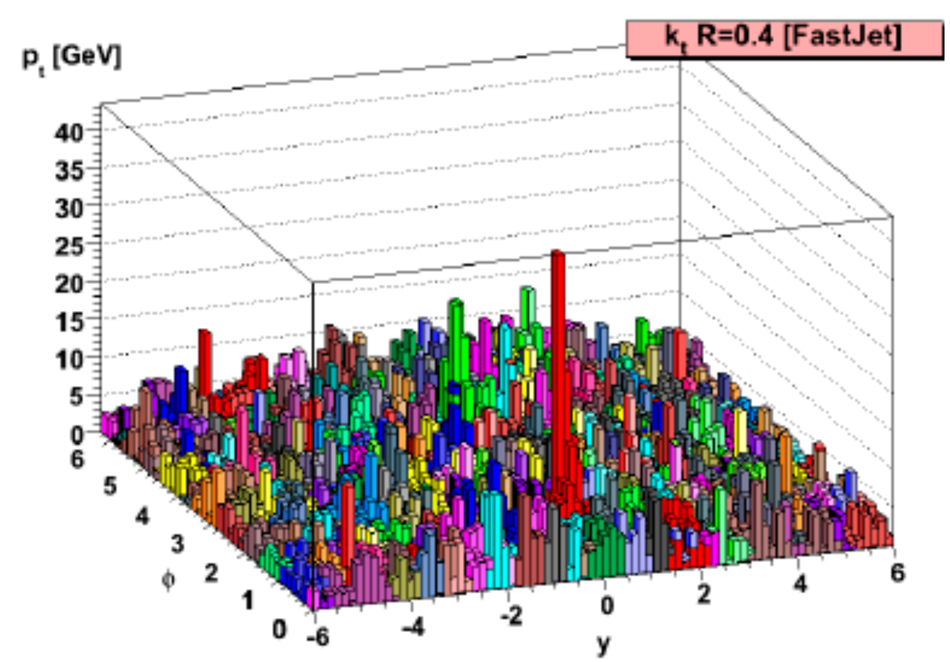
- Techniques for background substraction (the underlying event), designed to deal with the pileup at the LHC, can be applied in HI.
- Note: typically several 100 GeV are deposited per unit in η×Φ.



An example hard event

$p_t \sim 100$ GeV

Generated with Pythia

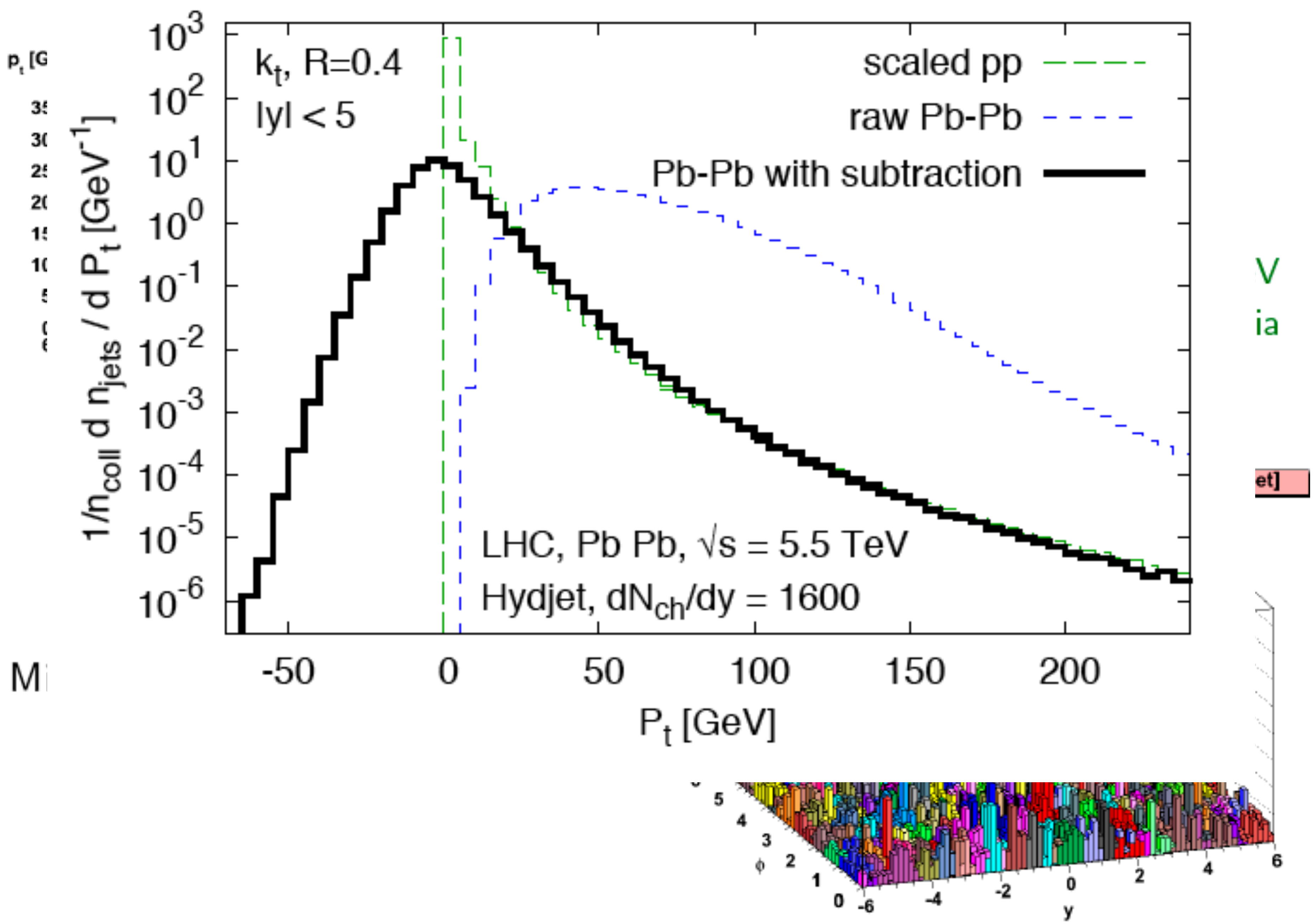


Mixed into LHC HI environment

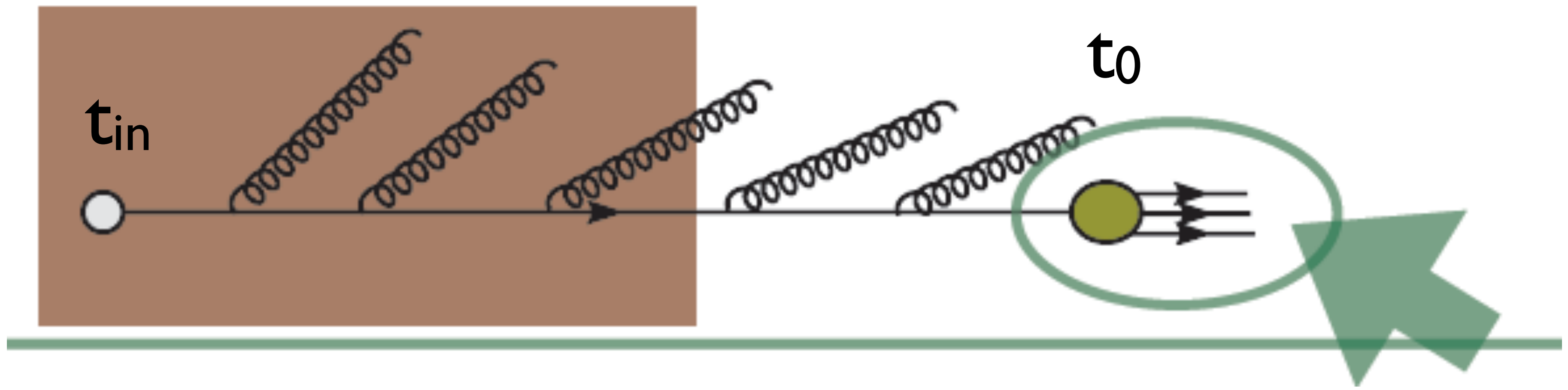
HydJet, $dN_{ch}/dy \simeq 1600$

Jets (II):

- Techniques for background substraction (the underlying event), designed to deal with the pileup at the LHC, can be applied in HI.
- Note: typically several 100 GeV are deposited per unit in η×Φ.



Monte Carlo (I):



• Assumption: hadronization is not affected by the medium: looks OK at RHIC for p_T>7-10 GeV.

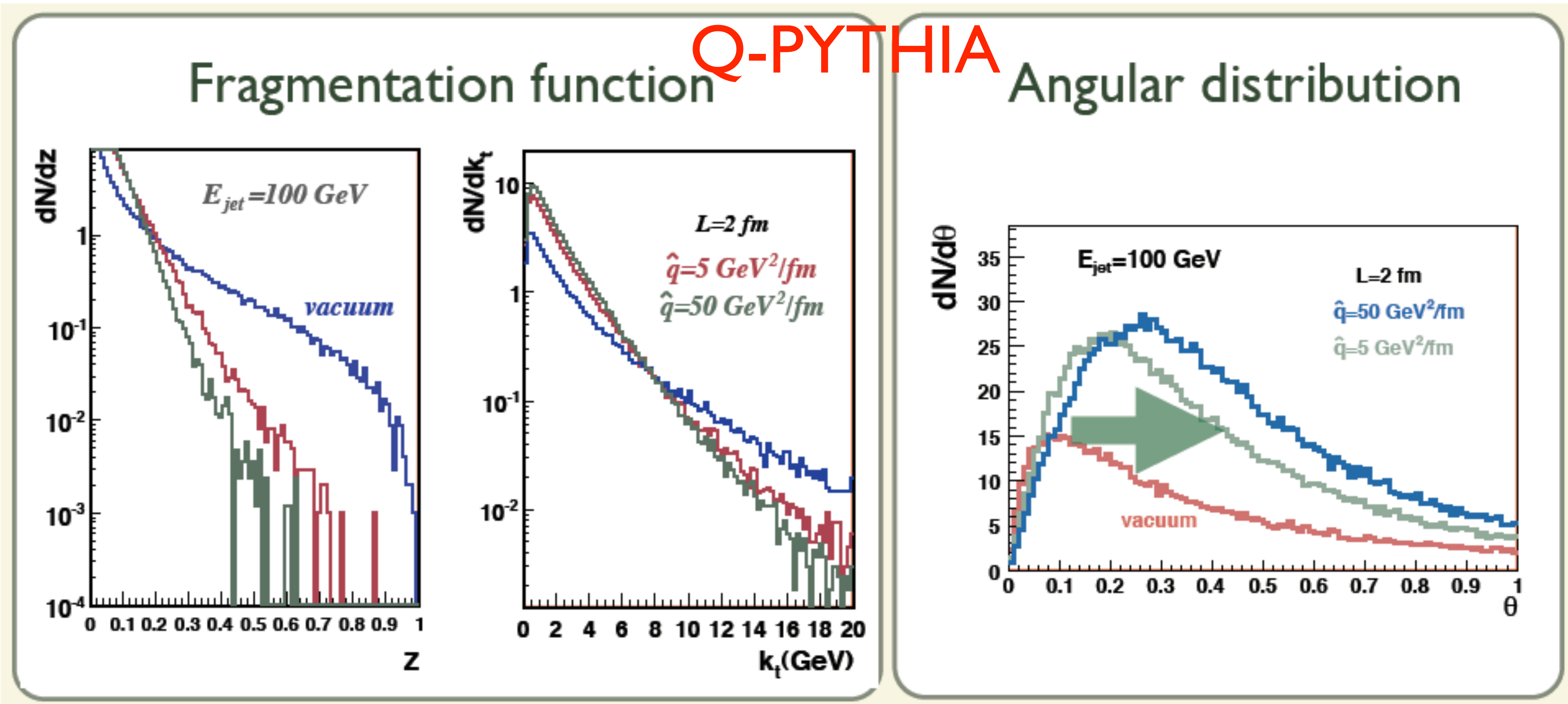
• The splittings are modified: either radiatively (Q-PYTHIA) or radiative+collisionally (JEWELL, PYQUEN); or the evolution is enlarged due to momentum broadening (YaJEM).

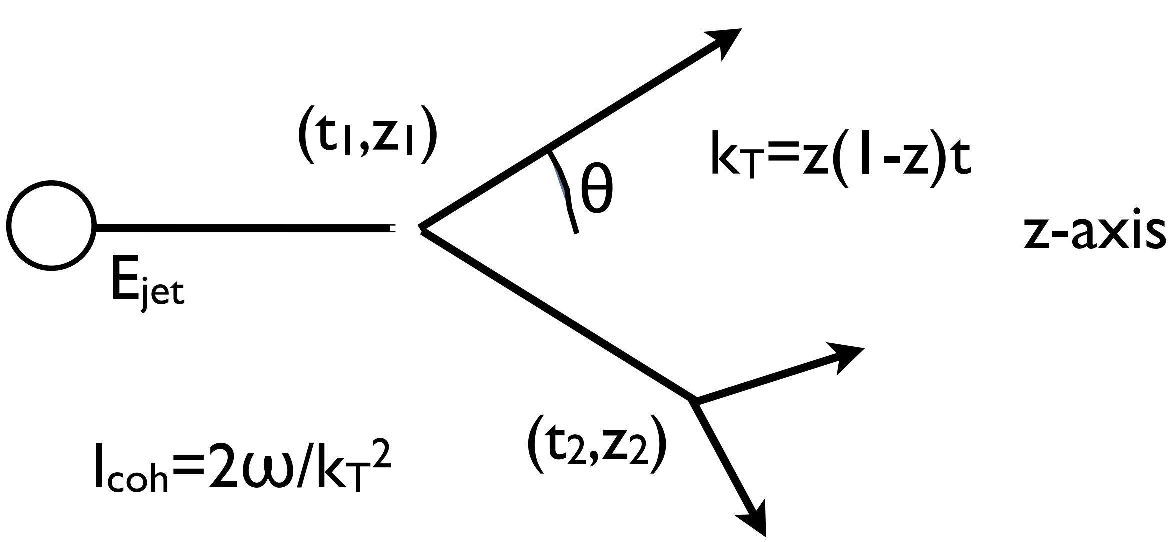
• Underlying ingredients: factorization no emission/emission/no emission/... (Sudakov/splitting/Sudakov/...) holds in the medium, and the evolution scale (t, k_T, Θ) can be related with the medium length → both to be proved (Jet Calculus in a medium).

Monte Carlo (II):

- The MC's generically reproduce the expectations:
  → Particle spectrum softens (jet quenching).
  → Emission angle enlarges (jet broadening).
  → Intra-jet multiplicity enlarges.

Monte Carlo (II):





- Intense activity at RHIC and the LHC: jet reconstruction in a large background (small clustering parameters versus out-of-'cone' medium modification).

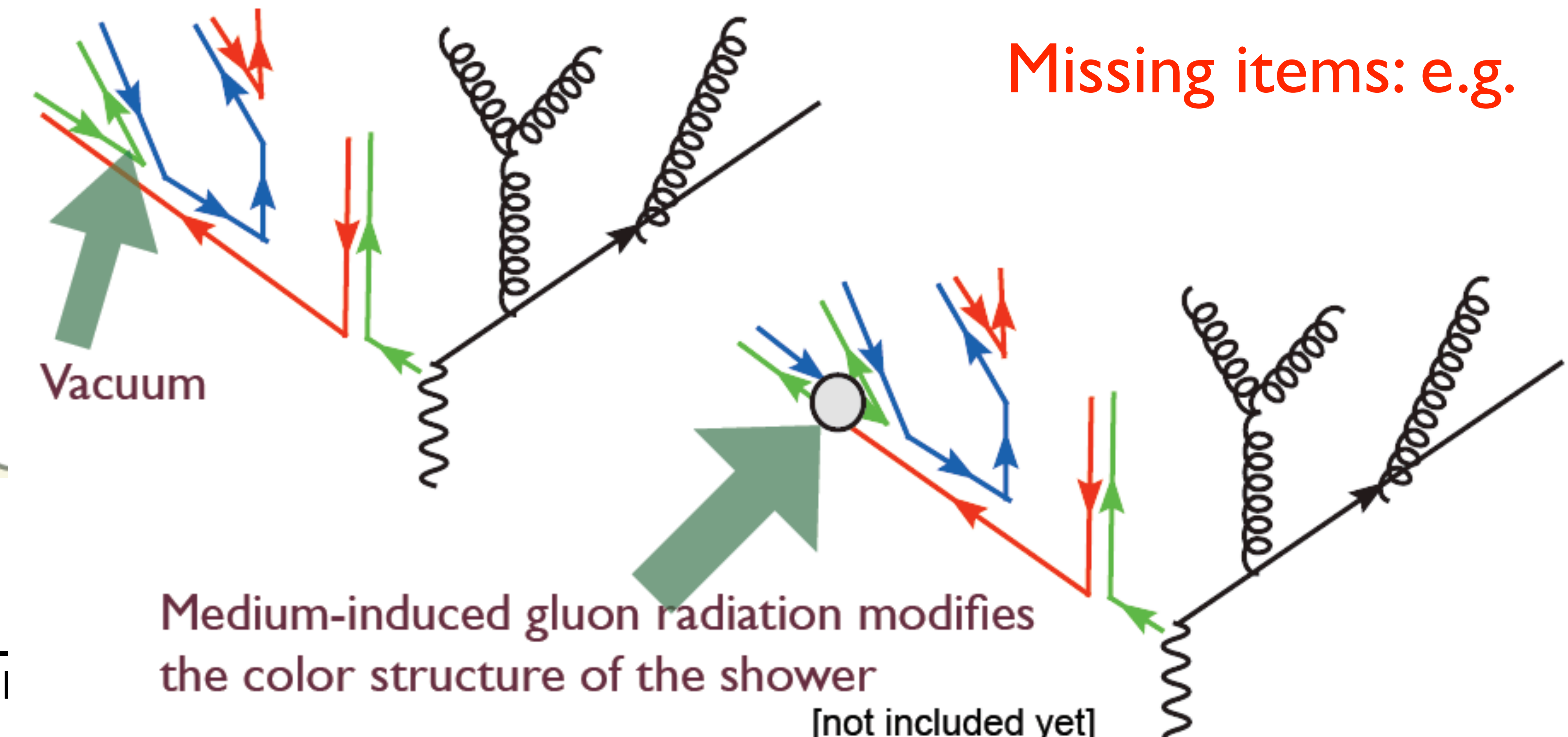
Monte Carlo (II):

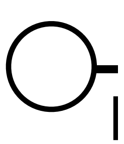
Q-PYTHIA

Fragmentation function

Angular distribution

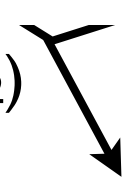
Missing items: e.g.





$l_{coh}=2\omega/k_T^2$

(t_2,z_2)



parameters versus out-of- cone
medium modification).